

Enabling Health Care Decisionmaking through Clinical Decision Support and Knowledge Management

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Structured Abstract

Objectives: The goals of this report were (1) to identify and systematically review the best evidence on clinical decision support systems (CDSSs) and knowledge management systems (KMSs) with regard to clinical effectiveness and factors/features that impact CDSSs/KMSs success and (2) to delineate areas for future research that will fill gaps in the published literature.

Data Sources: MEDLINE®, CINAHL®, PsycINFO®, and Web of Science.

Review Methods: We included studies published in English from 1976 through 2010. Three reviewers independently screened titles and abstracts, and five percent of the abstracts were randomly selected for rescreening by a second reviewer. At the full-text stage, paired researchers independently reviewed the articles and selected studies to be included. Bibliographies of included studies were manually examined for additional articles. Included articles were subsequently abstracted by two reviewers to create the evidence tables from which we formulated the content of this report. Meta-analyses were performed for the seven domains in which sufficient studies with common outcomes were included.

Results: The literature search identified 13,752 articles from which 131 randomized control trials (RCTs) were selected for inclusion. RCTs comprised 49 percent of the comparative studies on CDSSs/KMSs. We determined that both commercially and locally developed CDSSs deployed in many venues effectively improve process measures related to performing preventive services (OR 1.37, CI 1.16 to 1.62), ordering clinical studies (OR 2.04, CI 1.49 to 2.81), and prescribing therapies (OR 1.55, CI 1.28 to 1.89). Of the 14 CDSS features assessed in this review, the meta-analyses identified several new factors/features that were correlated with the success of CDSSs across all endpoints: integration with charting or order entry system to support workflow, promotion of action rather than inaction, no need for additional clinician data entry, and local user involvement in the development process. Three previously identified successful features of CDSS were also confirmed. We identified only 25 RCTs assessing the impact of CDSSs on clinical outcomes, 20 assessing costs, and 2 assessing KMSs on any outcomes.

Conclusions: Strong evidence now shows that CDSSs are effective in improving process measures across diverse academic and nonacademic settings using both commercially and locally developed systems. Evidence for the effectiveness of CDSSs on clinical outcomes and costs and KMSs on any outcomes is minimal, and more studies are needed in these areas. Four features of CDSSs that correlate with a successful impact of clinical decision support have been newly identified, and three previously identified features have been confirmed.

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Effective Health Care

Enabling Health Care Decisionmaking Through Clinical Decision Support and Knowledge Management

Executive Summary

Background

Efforts to improve the quality and value of health care are increasingly emphasizing a critical role for the meaningful use of clinical decision support systems (CDSSs). Examples of electronic CDSSs include alerts, reminders, computer-assisted diagnosis, order sets, drug-dosage calculations, and care-summary dashboards that provide performance feedback on quality indicators or benchmarks. The objective of a CDSS is to apply clinical knowledge in the context of patient-specific information to aid clinicians in the process of making decisions. As a form of health information technology, CDSSs can serve as an information tool to align clinician decisionmaking with best practice guidelines and evidence-based medical knowledge at the point of care as well as assist with information management to support clinicians' decisionmaking abilities. Ultimately, when used effectively, CDSSs can reduce workloads and improve both the quality of the health care outcomes and the efficiency of care delivery. However, in order to improve the quality of health care, CDSSs need to be effectively integrated into the process of routine care so that the right action to take becomes the easiest action to take and the action best supported by clinical evidence. In spite of the increasing emphasis on the role of CDSSs in improving care and lowering costs, substantial evidence supporting the widespread general use of CDSSs is still lacking. Until recently, most of the studies of CDSSs have arisen out of four clinical settings. Additionally, few studies report the ways in which CDSSs can be used optimally or about the features of CDSSs that lead to effective, sustained impact across a variety of clinical settings. Accordingly, a systematic review of the best research literature pertaining to CDSSs is warranted in order to determine what is known about CDSSs and what is lacking in our current understanding.

Objectives

This evidence report is part of a three-report series focusing on the strategic goals of the Agency for Healthcare Research and Quality's (AHRQ's) health information technology portfolio. The first report is addressing the use of health information technology to improve the quality and safety of medication management, and the second report is investigating the use of health information technology to support patient-centered care, coordination of care, and electronic exchange of health information to improve quality of care. This report specifically explores facilitating health care decisionmaking through health information technology. Supporting health care decisionmaking is a core element of the meaningful use criteria for electronic health records (EHRs). As the expected level of sophistication of EHRs increases in the evolving definitions of meaningful use, the need for more sophisticated CDSSs is imperative, as is the need for better operational use of these systems. This increasing importance of CDSSs acknowledges that EHRs alone are not an end in themselves but are instead a tool to augment the delivery of safe, evidence-based, high-quality health care through more consistent and sound decisionmaking.

The goals of this report were to summarize the available evidence related to CDSSs and knowledge management systems (KMSs), highlight the limitations of the evidence, and identify areas for future research.

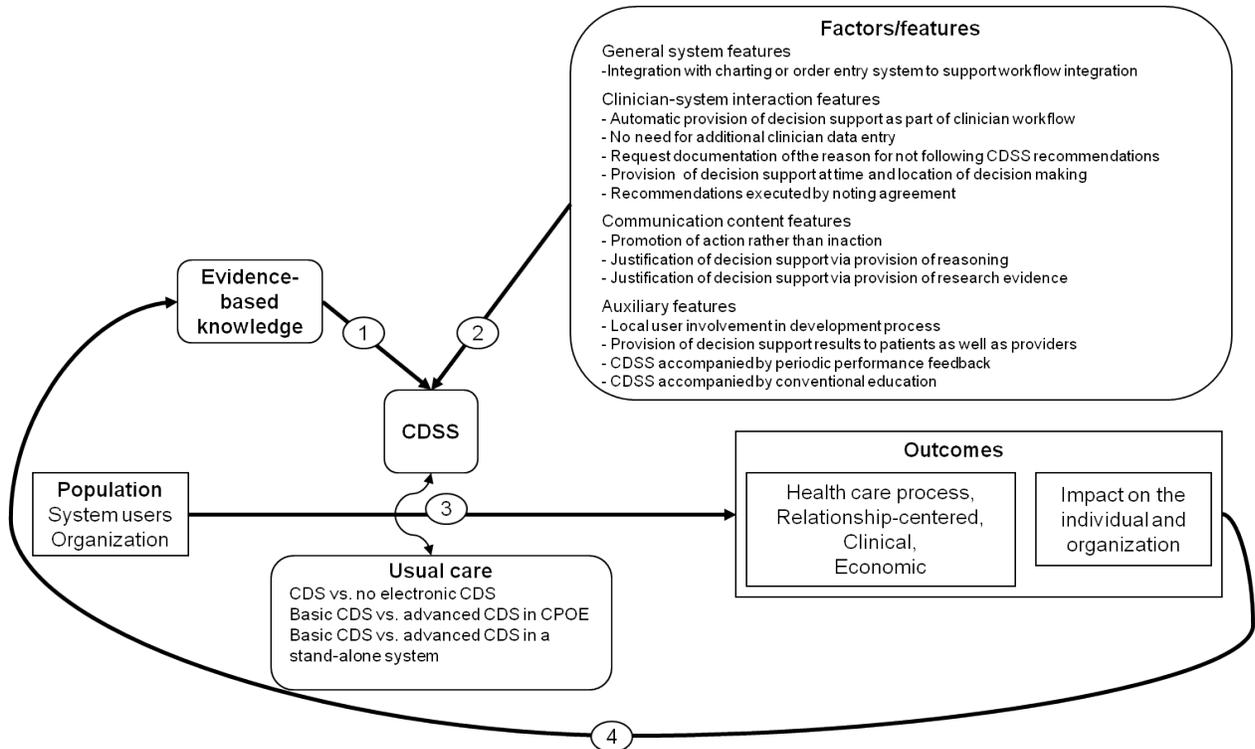
The key questions considered in this systematic review are:

- **Key Question 1:** What evidence-based study designs can be used to determine the clinical effectiveness of CDSSs?
- **Key Question 2:** What contextual factors/features influence the implementation and use of electronic knowledge management and CDSSs?
- **Key Question 3:** What is the impact of introducing electronic knowledge management and CDSSs?
 - 3a. Changes in the organization of health care delivery
 - 3b. Changes in the workload and efficiency for the user
 - 3c. Changes in process and clinical outcomes
- **Key Question 4:** What generalizable knowledge can be integrated into electronic knowledge management and CDSSs to improve health care quality?
 - 4a. Knowledge from published evidence about electronic knowledge management and CDSSs to improve health care quality based on different types of measures (health care process, relationship-centered, clinical, economic)
 - 4b. How a clinician's expertise/proficiency/informatics competency using the electronic knowledge management and CDSS affects patient outcomes (one type of measure)

Analytic Framework

The analytic framework (Figure ES-1) illustrates (1) how CDSS/KMS implementation and use is affected by evidence-based knowledge and contextual factors/features and (2) how interactions with CDSSs/KMSs by system users and health care organizations may result in outcomes such as changes in the individual, changes in the organization, and changes in health care quality.

Figure ES-1. Analytic Framework



Alternate text for Figure ES-1: The analytic framework illustrates (1) how CDSS/KMS implementation and use is affected by evidence-based knowledge and contextual factors/features and (2) how interactions with CDSSs/KMSs by system users and health care organizations may result in outcomes such as changes in the individual, changes in the organization, and changes in health care quality.

Methods

1. **Input from Stakeholders.** We identified experts in the field of CDSS and knowledge management to serve as members of the project’s Technical Expert Panel (TEP). The TEP contributes to AHRQ’s broader goals of (1) creating and maintaining science partnerships and public–private partnerships and (2) meeting the needs of an array of potential customers and users of this report. To ensure accountability and scientifically relevant work, we asked the TEP for input at key stages of the project. More specifically, TEP members participated in conference calls and email exchanges to refine the analytic framework and key questions at the beginning of the project, refine the scope, discuss inclusion and exclusion criteria, and provide advice on methodology. An additional group of peer reviewers was identified to provide comments on the report. Peer reviewers differed from the TEP members in that they were not involved during the project development phase of the project. The report will also be posted for public comment. A summary of the comments and their disposition from peer and public reviewers will be prepared and submitted to AHRQ.

2. **Data Sources and Selection.** The comprehensive literature search included electronic searching of peer-reviewed literature databases. These databases included the Cumulative Index to Nursing and Allied Health Literature (CINAHL®), Cochrane Database, MEDLINE® accessed via PubMed®, PsycINFO®, and Web of Science®. Searches of these databases were supplemented with manual searching of reference lists contained in all included articles and in relevant review articles. Search strategies were specific to each database in order to retrieve the articles most relevant to the key questions. Our basic search strategy used the National Library of Medicine’s Medical Subject Headings (MeSH) key word nomenclature developed for MEDLINE, limited to articles published in English, and a manual search of retrieved articles and published reviews. Search terms and strategies were developed in consultation with a medical librarian and included terms for evaluation and study types, clinical decision support systems, knowledge management systems, and computerized interaction.

Table ES-1 shows the inclusion and exclusion criteria for the key questions.

Table ES-1. Inclusion and Exclusion Criteria

Category	Criteria
Study population	KQs 1–4: <ul style="list-style-type: none"> • System user, defined as a health care provider (HCP) who interacts with the KMS or CDSS. Includes nurses, nurse practitioners, care managers, physician assistants, training MDs (residents, fellows), attending physicians or general practitioners, pharmacists. • Health care organization, defined as an organization that provides access to health care services delivered by medical and allied health professionals. Includes academic and community settings, clinics, practices, hospitals, long-term care facilities.

Category	Criteria
Study design	KQ 1: All study designs KQs 2-4: Randomized controlled trials (parallel group, crossover, cluster)
Factors/interventions	KQs 1–4: Implemented electronic KMS and CDSS (see Table 3)
Comparator	KQs 1–4: <ul style="list-style-type: none"> • CDSSs/KMSs are compared with no electronic CDSS/KMS • Basic CDSS is compared with advanced CDSS in computerized physician order entry (CPOE) or EHR • Basic CDSS is compared with advanced CDSS in a standalone system
Study outcomes	KQs 1-4: <ul style="list-style-type: none"> • Impact on clinical outcomes (length of stay, morbidity, mortality, measure of health-related quality of life, adverse events) • Impact on health care process outcomes (recommended preventive care, clinical study, or treatment was ordered/completed and adhered to) • Impact on workload, efficiency, and organization of health care delivery (number of patients seen, clinician workload, efficiency) • Impact on relationship-centered outcomes (patient satisfaction) • Impact on economic outcomes (cost and cost-effectiveness) • Impact on HCP use and implementation (acceptance, satisfaction, use, implementation)
Timing	No restrictions
Setting	No restrictions
Publication languages	English only
Admissible evidence (study design and other criteria)	KQs 1–4: <ul style="list-style-type: none"> • Study must report one or more outcomes of interest (see above criteria) • Study must report original data • Study must report sufficient details for data extraction and analysis • Intervention must be implemented in a real clinical setting • Intervention must be aimed at health care providers • Intervention must be used to aid decisionmaking at the point of care or for a specific care situation • Study must evaluate the effectiveness of KMS or CDSS
Exclusions	<ul style="list-style-type: none"> • Exclude studies of closed-loop systems that do not involve a provider • Exclude studies of systems that require mandatory compliance with the CDSS intervention, defined as when the clinician at the point of care is not given a choice on whether to follow the CDSS recommendations (compliance is mandated by the study protocol) • Exclude if the study evaluates only the performance of the system as opposed to the impact on clinical practice

Abbreviations: CDSS = clinical decision support system, CPOE = computerized physician order entry, EHR = electronic health record, HCP = health care provider, KMS = knowledge management system

Using the prespecified inclusion and exclusion criteria, titles and abstracts were examined independently by three reviewers for potential relevance to the key questions. Articles included by any reviewer underwent full-text screening. After the independent abstract screening stage by a single reviewer, five percent of the abstracts were randomly selected using a random number generator for a rescreen by a second reviewer. At the full-text screening stage, two independent reviewers read each article to determine if it met eligibility criteria. When the paired reviewers arrived at different decisions about whether to include or exclude an article, they reconciled the difference through a third-party arbitrator. Articles meeting our eligibility criteria were included for data abstraction.

3. **Data Extraction and Quality Assessment.** Data from published reports were abstracted into evidence tables by one reviewer and overread by a second reviewer. Data elements abstracted included descriptors to assess applicability, quality elements, intervention details, and outcomes. We examined 14 factors/features of a successful CDSS identified in a previous 2005 review and specific characteristics of those interventions. Disagreements were resolved by consensus or by obtaining a third reviewer's opinion when consensus could not be reached. The final evidence tables are intended to provide sufficient information so that readers can understand the study and determine its quality.

The included studies were assessed on the basis of the quality of their reporting of relevant data. We evaluated the quality of individual studies using the approach described in AHRQ's *Methods Guide for Effectiveness and Comparative Effectiveness Reviews*. To assess methodological quality, we employed the strategy to (1) apply predefined criteria for quality and critical appraisal and (2) arrive at a summary judgment of the study's quality. To indicate the summary judgment of the quality of the individual studies, we used the summary ratings of Good, Fair, or Poor. To assess applicability, we identified specific issues that may limit the applicability of individual studies or a body of evidence. The strength of evidence for each key question was evaluated using the four required domains: risk of bias, consistency, directness, and precision. Additionally, when appropriate, the studies were evaluated for coherence, dose-response association, residual confounding, strength of association (magnitude of effect), publication bias, and applicability. The strength of evidence was assigned an overall grade of High, Moderate, Low, or Insufficient.

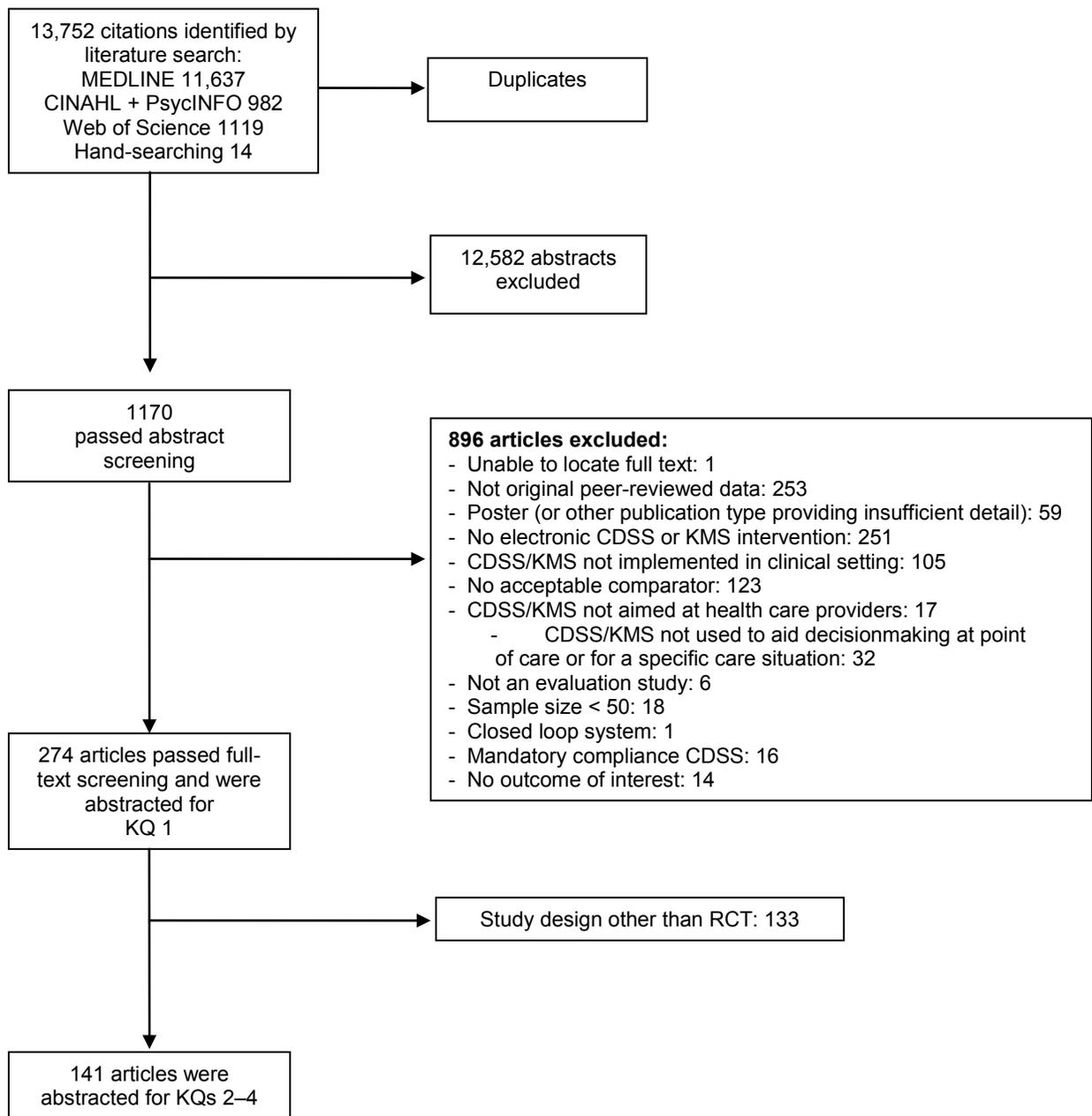
4. **Data Synthesis and Analysis.** Given that many studies did not have the statistical power to determine the benefit for the outcomes relevant to this review (which were often not the primary outcomes evaluated by study investigators), we considered synthesis (meta-analysis) in an attempt to overcome the type II error. We considered groups of studies to be suitable candidates for a quantitative synthesis when we were able to identify at least four studies that assessed the same outcome which could be expressed using a common endpoint. Estimates of parameters for the meta-analyses were combined using an empirical Bayes random-effects estimator. Most endpoints were combined using odds

ratios, especially when event rates that approached 1.0 were involved. However, the clinical endpoints such as morbidity, mortality, and length of stay were combined using relative risks. For these endpoints, the event rates were low, and some of the studies reported risk ratios instead of relative risks.

Results

We identified 13,752 citations from all sources (after removing duplicates). After applying inclusion/exclusion criteria at the title-and-abstract level, 1170 full-text articles were retrieved and screened. Of these, 896 articles were excluded at full-text review, with 274 articles remaining for data abstraction. Of these, 274 articles were abstracted for Key Question 1 (representing 264 unique studies), and 141 articles (representing 131 unique studies) for Key Questions 2 through 4. The flow of articles through the literature search and screening process is depicted in Figure ES-2.

Figure ES-2. Literature Search Flow



Alternate text for Figure ES-2: This figure shows the flow of articles through the literature search and screening process. We identified 13,752 citations from all sources (after removing duplicates). After applying inclusion/exclusion criteria at the title-and-abstract level, 1170 full-text articles were retrieved and screened. Of these, 896 articles were excluded at full-text review, with 274 articles remaining for data abstraction. Of these, 274 articles were abstracted for Key Question 1 (representing 264 unique studies), and 141 articles (representing 131 unique studies) for Key Questions 2 through 4.

Table ES-2 provides an aggregated view of the strength of evidence and brief conclusions from this review.

Table ES-2. Summary of Findings

Key Question	Level of Evidence	Conclusions
<p>Key Question 1: What evidence-based study designs can be used to determine the clinical effectiveness of CDSSs?</p>	<p>High</p>	<ul style="list-style-type: none"> • 264 studies were reviewed including 131 RCTs (49.6%), 99 quasi-experimental (37.5%), and 34 observational studies (12.9%) • Clinical and health care process outcomes were frequently reported in all three study design types: <ul style="list-style-type: none"> ○ Clinical outcomes (25.2% of RCTs, 31.3% of quasi-experimental, and 38.2% of observational studies) ○ Health care process outcomes (87.0% of RCTs, 73.7% of quasi-experimental, 67.6% for observational studies) • When RCT studies are impractical to conduct, well-designed quasi-experimental and observational studies can be used to evaluate the clinical effectiveness of CDSS.
<p>Key Question 2: What contextual factors/features influence the implementation and use of electronic knowledge management and CDSSs?</p>	<p>Moderate</p>	<ul style="list-style-type: none"> • Using meta-analysis on studies that evaluated adherence to preventative care (22 studies), clinical study (17 studies), and treatment as an outcome (39 studies), we confirmed 3 previously reported features associated with successful CDSS implementation and identified 4 additional features. • Our meta-analysis confirmed 3 previously reported factors/features were strongly associated with successful CDSS implementation: <ul style="list-style-type: none"> ○ Automatic provision of decision support as part of clinician workflow (OR of 1.38, 95 CI of 1.13 to 1.68 for adherence to preventative care, OR of 2.05, 95 CI of 1.53 to 2.73 for ordering of clinical studies, OR of 1.55, 95 CI of 1.24 to 1.95 for prescribing or ordering of therapy) ○ Provision of decision support at time and location of decisionmaking (OR of 1.39, 95 CI of 1.17 to 1.65 for adherence to preventative care, OR of 2.09, 95 CI of 1.42 to 3.06 for ordering of clinical studies, OR of 1.72, 95 CI of 1.37 to 2.14 for prescribing or ordering of therapy) ○ Provision of a recommendation, not just an assessment (OR of 1.41, 95 CI of 1.11 to 1.80 for adherence to preventative care, OR of 2.49, 95 CI of 1.70 to 3.63 for ordering of clinical studies, OR of 1.61, 95 CI of 1.25 to 2.06 for prescribing or ordering of therapy) • The meta-analysis also identified 4 additional factors/features that were correlated with the success of CDSSs:

Key Question	Level of Evidence	Conclusions
		<ul style="list-style-type: none"> ○ Integration with charting or order entry system to support workflow integration (OR of 1.48, 95 CI of 1.06 to 2.06 for adherence to preventive care, OR of 1.67, 95 CI of 1.49 to 2.81 for ordering of clinical studies, OR of 1.61, 95 CI of 1.28 to 2.03 for prescribing or ordering of therapy) ○ Promotion of action rather than inaction (OR of 1.28, 95 CI of 1.08 to 1.52 for adherence to preventive care, OR of 1.64, 95 CI of 1.25 to 2.16 for ordering of clinical studies, OR of 1.56, 95 CI of 1.18 to 2.07 for prescribing or ordering of therapy) ○ No need for additional clinician data entry (OR of 1.41, 95 CI of 1.08 to 1.84 for adherence to preventive care, OR of 1.71, 95 CI of 1.25 to 2.35 for ordering of clinical studies, OR of 1.71, 95 CI of 1.30 to 2.26 for prescribing or ordering of therapy) ○ Local user involvement in development process (OR of 1.49, 95 CI of 1.13 to 1.95 for adherence to preventive care, OR of 1.91, 95 CI of 1.12 to 3.04 for ordering of clinical studies, OR of 1.98, 95 CI of 1.40 to 2.78 for prescribing or ordering of therapy) <ul style="list-style-type: none"> ● Many of the studies included more than one feature/factor and because the studies did not specifically evaluate whether the systems with and without an individual factor/feature differed in terms of their impact on the outcome of interest, it is difficult to determine the importance of individual factors/features.
Key Question 3: What is the impact of introducing electronic knowledge management and CDSSs?		
(a) Changes in the organization of health care delivery	Insufficient	<ul style="list-style-type: none"> ● Of the eligible studies, none examined the impact of CDSSs/KMSs on changes in the organization of health care delivery.
(b) Changes in the workload and efficiency for the user		
a. Number of patients seen/unit time	Insufficient	<ul style="list-style-type: none"> ● Of the eligible studies, none examined the impact of CDSSs/KMSs on the number of patients seen/unit time.
b. Clinician workload	Insufficient	<ul style="list-style-type: none"> ● Of the eligible studies, none examined the impact of CDSSs/KMSs on clinician workload.

Key Question	Level of Evidence	Conclusions
c. Efficiency	Insufficient	<ul style="list-style-type: none"> We included 5 studies (3.8%) (including three good-quality studies) that examined the impact of CDSSs/KMSs on efficiency. From these studies there is limited evidence that CDSSs that provided decision support recommendations to providers synchronously at the point of care trended toward improvement in efficiency.
(c) Changes in process and clinical outcomes		
<i>Process outcomes:</i>		
a. Recommended preventative care service ordered/completed	High	<ul style="list-style-type: none"> 40 of our included studies (30.5%) examined the impact of CDSSs/KMSs on ordering or completing recommended preventative care services. This set of studies included 18 good-quality, 157 fair-quality, and 7 poor-quality studies. A meta-analysis of 22 studies (55.0%) which provided sufficient data to calculate a common endpoint indicated that CDSSs increase preventative care service ordered/completed with an odds ratio of 1.37 (95% confidence interval 1.16 to 1.62). CDSSs that demonstrated an impact on the appropriate ordering preventative care procedures were conducted in both the academic and community ambulatory setting, were locally developed, automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care and did not require a mandatory clinician response.
b. Recommended clinical study ordered/completed	Moderate	<ul style="list-style-type: none"> 24 of our included studies (18.3%) examined the impact of CDSSs/KMSs on the ordering and completion of recommended clinical studies. This set of studies included 14 good-quality, 6 fair-quality, and 4 poor-quality studies. A meta-analysis of 17 studies (70.8%) which provided sufficient data to calculate a common endpoint indicated that CDSSs increase appropriate clinical studies ordered/completed with an odds ratio of 2.04 (95% confidence interval 1.49 to 2.81). Although there was strong evidence from studies conducted in the academic and community ambulatory settings that CDSSs integrated in CPOE or EHR systems, locally developed CDSSs that provided recommendations to providers synchronously at the point of care and did not require a mandatory clinician response are effective at improving appropriate ordering of clinical studies; 2 of

Key Question	Level of Evidence	Conclusions
		the 3 key papers reported a negative impact of CDSSs on the ordering of clinical studies and therefore, our confidence in the impact is lessened.
c. Recommended treatment ordered/prescribed	High	<ul style="list-style-type: none"> • 61 of our included studies (46.6%) examined the impact of CDSSs/KMSs on the ordering or prescribing of therapy. This set of studies included 36 good-quality, 17 fair-quality, and 8 poor-quality studies. • A meta-analysis of the 39 studies (63.9%) which provided sufficient data to calculate a common endpoint indicated that CDSSs increase treatment ordered/prescribed with an odds ratio of 1.55 (95% confidence interval 1.28 to 1.89). • CDSSs that improved treatment ordering/prescribing were implemented in academic and community ambulatory settings, were system-integrated, locally developed, provided recommendations to providers synchronously at the point of care and did not require a mandatory clinician response.
d. Impact on user knowledge	Insufficient	<ul style="list-style-type: none"> • 5 of our included studies (3.8%) examined the impact of CDSSs/KMSs on user knowledge. This set of studies included 0 good-quality, 4 fair-quality, and 1 poor-quality studies
<i>Clinical outcomes:</i>		
a. Morbidity	Moderate	<ul style="list-style-type: none"> • 25 of our included studies (19.1%) examined the impact of CDSSs/KMSs on morbidity. This set of studies included 14 good-quality, 9 fair-quality, and 2 poor-quality studies. • A meta-analysis of 15 studies (60%) that provided sufficient data to calculate a common endpoint indicated a combined relative risk of 0.934 (95% CI 0.867 to 1.006). • There is modest evidence from the academic setting that CDSSs that provided recommendations to providers synchronously at the point of care are effective or demonstrated a trend towards a reduction in patient morbidity.
b. Mortality	Low	<ul style="list-style-type: none"> • 6 of our included studies (4.6%) examined the impact of CDSSs/KMSs on mortality. All studies in this set were rated as good quality. • A meta-analysis of the 6 studies (100%) reported a combined relative risk of 0.9048 (95% CI 0.7564 to 1.082). • Although all of the studies were high-quality, less than half of the studies were

Key Question	Level of Evidence	Conclusions
c. Length of stay	Low	<p>evaluated for at least a year or with more than 2000 patients.</p> <ul style="list-style-type: none"> • 5 of our included studies (3.8%) examined the impact of CDSSs/KMSs on length of stay. All studies in this set were rated as good quality. • A meta-analysis of 4 studies (80%) which provided sufficient data to calculate a common endpoint indicated a combined relative risk of 0.977 (95% CI 0.884 to 1.081). • There is limited evidence from the academic setting that CDSSs that automatically delivered system-initiated recommendations synchronously at the point of care trends toward reducing length of stay.
d. Health-related quality of life	Low	<ul style="list-style-type: none"> • 5 of our included studies (3.8%) examined the impact of CDSSs/KMSs on health-related quality of life. This set of studies included 2 good-quality, 2 fair-quality, and 1 poor-quality studies. • The majority of these studies were evaluated for at least a year, and all included a sample size between 500 and 1000. • There is limited evidence from the ambulatory setting that system-integrated, locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrate a trend toward higher quality of life scores.
e. Adverse events	Low	<ul style="list-style-type: none"> • 6 of our included studies (4.6%) examined the impact of CDSSs/KMSs on health-related quality of life. This set of studies included 4 good-quality, 12 fair-quality, and 1 poor-quality studies. • A meta-analysis of the 6 studies (100%) reported a combined relative risk of 0.923 (95% CI 0.770 to 1.107). • Although the majority of the studies were high-quality, the majority of these studies were evaluated for less than a year and did not include a sample size larger than 2000 patients. • There is limited evidence from the academic setting that system-integrated CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrate an effect on reducing or preventing adverse events.

Key Question	Level of Evidence	Conclusions
<i>Economic outcomes:</i>		
a. Cost	Low	<ul style="list-style-type: none"> • 20 of our included studies (15.3%) examined the impact of CDSSs/KMSs on cost. This set of studies included 9 good-quality, 6 fair-quality, and 5 poor-quality studies. • The majority of these studies were evaluated for less than 1 year and included less than 2000 patients. • CDSSs from the inpatient and ambulatory settings that were locally developed and that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrated a trend toward lower treatment costs and total costs and greater cost-savings than the control groups and other non-CDSS intervention groups.
b. Cost-effectiveness	Insufficient	<ul style="list-style-type: none"> • 6 of our included studies (4.6%) examined the impact of CDSSs/KMSs on cost effectiveness. This set of studies included 1 good-quality, 5 fair-quality, and 0 poor-quality studies. • There is conflicting evidence from the ambulatory setting regarding the cost effectiveness of CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care. Some studies demonstrated a trend toward cost-effectiveness, however one of the included key papers reported a negative impact of CDSSs on cost-effectiveness and therefore, our confidence in the impact is additionally lessened.
<i>Use and implementation outcomes:</i>		
a. HCP acceptance	Low	<ul style="list-style-type: none"> • 22 of our included studies (16.8%) examined the impact of CDSSs/KMSs on HCP acceptance. This set of studies included 9 good-quality, 10 fair-quality, and 3 poor-quality studies. • Studies suggested that high levels of acceptance (acceptance rate greater than 75%) of recommendations from CDSSs that automatically delivered system-initiated (push) recommendations to providers are the exception rather than the rule.
b. HCP satisfaction	Moderate	<ul style="list-style-type: none"> • 18 of our included studies (13.7%) examined the impact of CDSSs/KMSs on HCP satisfaction. This set of studies included 9 good-quality, 6 fair-quality, and 3 poor-quality studies. • The majority of these studies were evaluated for at less a year and only 10%

Key Question	Level of Evidence	Conclusions
		<p>included a sample size larger than 2,000 patients.</p> <ul style="list-style-type: none"> CDSSs that were well-received by providers were implemented within the academic and community ambulatory settings, were system-integrated, locally developed, automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care and did not require a mandatory clinician response.
c. HCP use	Low	<ul style="list-style-type: none"> 15 of our included studies (11.5%) examined the impact of CDSSs/KMSs on HCP use. This set of studies included 5 good-quality, 8 fair-quality, and 2 poor-quality studies. Only 2 of the included studies documented usage over 80%. Among studies evaluating clinical or economic outcomes, none of these studies demonstrated provider use of CDSSs greater than 80%.
d. Implementation	Insufficient	<ul style="list-style-type: none"> 3 of our included studies (2.3%) examined the impact of CDSSs/KMSs on HCP use. This set of studies included 0 good-quality, 1 fair-quality, and 2 poor-quality studies There is insufficient evidence of how CDSSs/KMSs impacted implementation in practice and no high-quality studies specifically examined this outcome.
<i>Relationship-centered outcomes:</i>		
Patient satisfaction	Insufficient	<ul style="list-style-type: none"> 7 of our included studies (5.3%) examined the impact of CDSSs/KMSs on patient satisfaction. This set of studies included 4 good-quality, 2 fair-quality, and 1 poor-quality studies. Although the majority of the studies were high-quality, there is conflicting evidence that CDSSs had a positive effect on patient satisfaction. While some studies did not find that provider use of CDSSs increased satisfaction with the care received or overall visit, there was evidence from studies with evaluation periods of at least 2 years that the intervention patients were more satisfied than those in the control group.

Key Question	Level of Evidence	Conclusions
Key Question 4: What generalizable knowledge can be integrated into electronic knowledge management and CDSSs to improve health care quality?		
(a) Knowledge from published evidence about electronic knowledge management and CDSSs to improve health care quality based on different types of measures (health care process, relationship-centered, clinical, economic)	Moderate	<ul style="list-style-type: none"> • The most common source of knowledge incorporated into CDSSs was derived from structured care protocols (60 studies, 45.8%) and clinical practice guidelines (33 studies, 25.2%) that focused on a single or limited set of medical conditions.
(b) How a clinician's expertise/proficiency/informatics competency using the electronic knowledge management and CDSS affects patient outcomes (one type of measure)	Insufficient	<ul style="list-style-type: none"> • Clinician expertise was not reported in 46 of the included studies (35.1%). In 35 studies (26.7%), CDSS recommendations were delivered using a paper-based format and so clinician expertise in using the CDSS was not relevant. • 50 studies (38.2%) reported data on clinician expertise in using CDSSs although the definition and reporting of this expertise was variable and the relationship between this expertise and patient outcomes was sparse.

Discussion

We conducted a systematic review of the indexed medical literature to identify the best evidence concerning the impact of CDSSs/KMSs on a broad set of outcomes. We also sought to identify gaps in the available evidence about the effectiveness of CDSSs/KMSs. We screened 13,752 abstracts and manuscripts dating to 1976, from which we identified 274 comparative studies— of which 131 were RCTs. Studies with similar outcomes and common endpoints were combined to conduct meta-analyses. This review investigated the continuum of information support for clinical care, including traditional CDSSs as well as information retrieval systems and knowledge resources developed for access at the point of care.

Using meta-analysis on studies that evaluated adherence to preventive care, clinical study, and treatment as an outcome, we confirmed three previously reported features associated with successful CDSS implementations and identified four additional features. These seven features included general system features, clinician-system interaction features, communication content features, and auxiliary features. These features were present across the breadth of CDSS implementations in diverse venues using both locally and commercially developed systems.

Summary of weaknesses or gaps in the evidence. With regard to outcomes, we discovered strong evidence that CDSSs that include the above features favorably impact care processes including prescribing treatments, facilitating preventive care services, and ordering clinical studies. This effect on processes spanned diverse venues and systems. In contrast to previous observations, where most reports of successful clinical decision support implementation were based on locally developed systems at four sites, this effect has now been observed at diverse community sites using commercially developed systems. We found, however, that evidence demonstrating positive effects of clinical decision support on clinical and economic outcomes remains limited. We also found limited evidence showing an impact of clinical decision support on clinical workload and efficiency.

In spite of a favorable trend to fill a gap identified in a previous evidence report that studied commercial CDSSs/KMSs in community settings, the literature is still lacking for evidence concerning the content of CDSSs, the recipients of clinical decision support, the types of outcomes reported in CDSS evaluations, and the issues related to implementation and deployment of CDSSs to support wide-scale application as expected for the meaningful use of EHRs.

Most of the published RCTs on CDSSs focused on a single or limited set of conditions. Studies are needed to determine how clinical decision support can be provided for multiple health issues simultaneously. Such studies will need to address reconciliation of advice across diverse combinations of comorbid conditions, prioritization of recommendations, and avoidance of “alert fatigue.” In a second issue related to CDSS/KMS content, we found a paucity of studies on KMS (only two RCTs identified). Accordingly, studies need to be initiated to generate rigorous evidence to determine how information retrieval systems and point-of-care knowledge resources can most effectively be used to improve health care.

With regard to the recipients of clinical decision support, most studies concentrated on decision support delivered to physicians. As health care migrates to more team-oriented delivery models, future studies will need to investigate which care team members should receive clinical decision support advice to optimize effectiveness.

In the area of outcomes, relatively few studies reported clinical outcomes and even fewer addressed the cost implications of clinical decision support. Outcome studies that explored the unintended consequences of decision support were also limited.

Finally, with regard to deficiencies in the best literature, we discovered relatively few RCTs that rigorously evaluated issues related to CDSS implementation, workflow, and the delivery of care. In a similar vein, we found few studies that investigated how CDSSs could be effectively ported to different settings. Most of the reports focused on the use of a CDSS at a single institution or closely related institutions. The portability issue will need to accommodate the discovery that user involvement in CDSS development is a feature associated with successful implementation.

Limitations of the review process. Our systematic review has several limitations. First, we acknowledge a publication bias in that studies with positive outcomes are more likely than negative studies to be reported in the medical literature. Accordingly, the literature favors features that lead to CDSS success and may underreport features that resulted in CDSS implementation failures.

A second limitation of the literature on clinical decision support is that the studies are extremely heterogeneous with regard to the systems, populations, settings, and outcomes. Consequently, it is difficult to derive general observations about CDSSs since each system and setting has unique characteristics that may be critical but not identified or transferable. We sought to minimize this limitation in our meta-analysis by including studies with a common endpoint within the outcome categories; still, it was difficult to isolate the effect of individual factors or features.

A third limitation is that we chose to concentrate primarily on RCTs for the bulk of the evidence for this report and thus excluded findings from quasi-experimental and observational studies. While RCTs provide the best evidence on CDSS effectiveness, these RCTs may provide less information regarding issues related to CDSS implementation, impact on workflow, and factors affecting usability.

A fourth limitation is related to the variable descriptions of intervention details provided in each publication. We abstracted specific data, pertaining to the design and user interaction with each system, that were commonly reported within informatics journal publications but which were less frequently described in clinically oriented publications. Conceivably, some studies did not report detailed system descriptions due to article length restrictions.

Implications for future research. Future research needs to investigate issues related to CDSS content, recipients, outcomes, and implementation. First in the area of CDSS content, CDSSs need to mature to the next generation in which the breadth of comorbid conditions for a given patient are routinely addressed. Such studies will need to explore how advice about multiple care issues and disparate CDSSs can be reconciled and how recommendations should be prioritized to avoid alert fatigue. Additionally, further investigation is needed to better understand how local adaptation of general knowledge integrated into CDSSs affects outcomes and provider acceptance; whether specific types of general knowledge are better-suited for implementation in CDSSs; and differences in the types of general knowledge contained in locally developed and commercially developed CDSSs and any potential differences in improvements health care quality. Along these lines, studies are also needed to determine how CDSS content can be delivered most effectively for each CDSS niche. Such studies can

determine if interruptive (pop-up alerts and reminders) or noninterruptive (order sets, smart forms, dashboards) are preferable as well as how the users should interact with the content from a specific type of CDSS: push versus pull, mandatory versus voluntary versus no user response, explanation versus no explanation for noncompliance, and so on.

Second, studies evaluating the impact of KMSs are needed across the board. The KMS field is in its infancy, and such studies need to demonstrate when and how knowledge retrieval systems and point-of-care knowledge references are effective and useful.

Future studies will also need to explore who the optimal recipients of clinical decision support advice should be. With the growth of team-based care delivery models, studies are needed to ascertain who on the team other than physicians should receive which type of advice and how the delivery of advice can be orchestrated to facilitate team-based care coordination.

More studies are needed to demonstrate how CDSSs impact hard clinical outcomes to make real differences in health and wellness and not just improve process measures. Additionally, the costs of CDSSs need to be investigated, and the economic attractiveness of CDSSs needs to be determined. The case needs to be made for cost-effectiveness and subsequent return on investment in order to promote and expand CDSS utilization. Future studies also need to explore the unintended consequences of CDSSs, particularly as multiple comorbid conditions are included and recommendations are delivered to multiple members of a care delivery team. As outcomes are measured with disparate CDSSs in diverse environments, the need to standardize metrics for workload, efficiency, costs, process measures, and clinical outcomes across systems will need to be addressed. Research is needed to determine what metrics best assess CDSS effectiveness and how these metrics can be standardized. Standardization of these outcomes and metrics will also facilitate the evaluation of CDSSs.

With regard to promoting extensive use of CDSSs, models for porting CDSSs across settings will need to be developed and evaluated. Studies will need to validate the concept of clinical decision support knowledge sharing across applications and institutions as proposed in recent position papers. Can centralized knowledge repositories be effective in meeting CDSS needs for the region or the nation as a whole? At the level of individual systems, it will be useful to identify which CDSS features genuinely make a difference in effectiveness and user satisfaction. From the analysis conducted through this report, we have identified a cluster of features that are associated with a favorable impact of a CDSS; however, the many features are interrelated and the available studies do not allow us to isolate individual features or even feature groups. As CDSSs become more ubiquitous, studies can be performed that assess CDSSs with and without selected features in order to determine with greater clarity the relative importance of individual features. In addition to the features of the CDSS itself, characteristics of the environment and workflow into which a CDSS is deployed and characteristics of the intended CDSS users need to be identified and investigated so that the impact of these characteristics on the success of the CDSS as can be determined. Well-described RCTs are most needed to investigate the impact of those characteristics; however, exploration into the strengths and limitations of the evidence provided by quasi-experimental and observational studies is also warranted. Once the system, environmental, workflow, and user characteristics are delineated with regard to their influence on CDSS effectiveness, the system, environment, workflow, and users can be proactively adapted to optimize CDSS integration.

Glossary

AHRQ	Agency for Healthcare Research and Quality
CI	confidence interval
CPOE	computerized physician/provider order entry
DVT	deep vein thrombosis
EHR	electronic health record
HCP	health care provider
HIT	health information technology
HRQOL	health-related quality of life
KMS	knowledge management system
OR	odds ratio
p	probability
PA	physician assistant
PCP	primary care physician
PE	pulmonary embolism
PICOTS	population, intervention, comparator, outcome, timing, setting
RCT	randomized controlled trial
RR	risk ratio

References

Please refer to the reference list in the full report for documentation of statements contained in the Executive Summary.

Internet Citation

Provided by AHRQ

Introduction

Background

This evidence report is part of a three-report series focusing on the strategic goals of the Agency for Healthcare Research and Quality's (AHRQ's) health information technology portfolio. The first report is addressing the use of health information technology to improve the quality and safety of medication management. The second report is investigating the use of health information technology to support patient-centered care, coordination of care, and electronic exchange of health information to improve quality of care. This report specifically explores facilitating health care decisionmaking through health information technology. Supporting health care decisionmaking is a core element of the meaningful use criteria for electronic health records (EHRs).¹ As the expected level of sophistication of EHRs increases in the evolving definitions of meaningful use, the need for more sophisticated clinical decision support systems (CDSSs) is imperative, as is the need for better operational use of these systems. This increasing importance of CDSSs acknowledges that EHRs alone are not an end in themselves but are instead a tool to augment the delivery of safe, evidence-based, high-quality health care through more consistent and sound decisionmaking.

Scope and Key Questions

Efforts to improve the quality and value of health care are increasingly emphasizing a critical role for the meaningful use of CDSSs. Examples of electronic CDSSs include alerts, reminders, computer-assisted diagnosis, order sets, drug-dosage calculations, and care-summary dashboards that provide performance feedback on quality indicators or benchmarks. The objective of clinical decision support is to apply clinical knowledge in the context of patient-specific information to aid clinicians in the process of making decisions. As a form of health information technology, CDSSs can serve as an information tool to align clinician decisionmaking with best practice guidelines and evidence-based medical knowledge at the point of care as well as assist with information management to support clinicians' decisionmaking abilities. Ultimately, when used effectively, CDSSs can reduce workloads and improve both the quality of the health care outcomes and the efficiency of care delivery.² However, in order to improve the quality of health care, CDSSs need to be effectively integrated into the process of routine care so that the right action to take becomes the easiest action to take and the action best supported by clinical evidence. In spite of the increasing emphasis on the role of CDSSs in improving care and lowering costs, substantial evidence supporting the widespread general use of CDSSs is still lacking. Until recently, most of the studies of CDSSs have arisen out of four benchmark settings (Brigham and Women's Hospital/Partners Health Care, Department of Veterans Affairs, LDS Hospital/Intermountain Health Care, and Regenstrief Institute).³ Additionally, few studies report the ways in which CDSSs can be used optimally or about the features of a CDSS that lead to effective, sustained impact across a variety of clinical settings. Accordingly, a systematic review of the best research literature pertaining to CDSSs is warranted in order to determine what is known about CDSSs and what is lacking in our current understanding.

The key questions considered in this systematic review are:

- **Key Question 1:** What evidence-based study designs can be used to determine the clinical effectiveness of CDSSs?
- **Key Question 2:** What contextual factors/features influence the implementation and use of electronic knowledge management and CDSSs?
- **Key Question 3:** What is the impact of introducing electronic knowledge management and CDSSs?
 - 3a. Changes in the organization of health care delivery
 - 3b. Changes in the workload and efficiency for the user
 - 3c. Changes in process and clinical outcomes
- **Key Question 4:** What generalizable knowledge can be integrated into electronic knowledge management and CDSSs to improve health care quality?
 - 4a. Knowledge from published evidence about electronic knowledge management and CDSSs to improve health care quality based on different types of measures (health care process, relationship-centered, clinical, economic)
 - 4b. How a clinician's expertise/proficiency/informatics competency using the electronic knowledge management and CDSS affects patient outcomes (one type of measure)

Purpose of This Report

The purpose of this report is to summarize the available evidence related to CDSSs and knowledge management systems (KMSs), highlight the limitations of the evidence, and identify areas for future research. To achieve these goals, we conducted a comprehensive systematic literature search, consulted with a Technical Expert Panel (TEP), reviewed and analyzed the existing evidence, and used the findings of this process to identify gaps in knowledge. The final product synthesizes results from the existing peer-reviewed research literature to address identified knowledge gaps and to provide critical information on developing and using electronic knowledge management and CDSS.

Role of the Technical Expert Panel

We identified experts in the field of CDSS and knowledge management to serve as members of the project's TEP. The TEP contributes to AHRQ's broader goals of (1) creating and maintaining science partnerships and public-private partnerships and (2) meeting the needs of an array of potential customers and users of this report. To ensure accountability and scientifically relevant work, we asked the TEP for input at key stages of the project. More specifically, TEP members participated in conference calls and email exchanges to refine the analytic framework and key questions at the beginning of the project, refine the scope, discuss inclusion and exclusion criteria, and provide advice on methodology.

Organization of This Report

This report is organized into five chapters. **Introduction** presents the topic and provides background justification for this systematic review. **Methods** describes the methods used to produce this report, including the four key questions addressed, the analytic framework, inclusion/exclusion criteria, search strategies, data abstraction and synthesis, and assessment of methodological quality. In **Results**, we report on the number of publications reviewed and present the results of our literature search and synthesis of the key questions. **Summary and Discussion** presents the main findings and provides a contextual reflection on the results obtained from the literature search and review, summarizes the gaps in the evidence, and describes limitations of the review process. **Future Research** synthesizes key knowledge gaps and existing peer-reviewed research to provide critical information on needed research related to the development and use of electronic knowledge management and clinical decision support.

Methods

In this chapter, we document the procedures used by the Evidence-based Practice Center (EPC) to develop this systematic review of the evidence regarding health care decisionmaking through clinical decision support and knowledge management systems. To provide a context for the review, we first describe the topic development and present the key questions and analytic framework. Next, we describe the methods used to identify articles relevant to our key questions, our inclusion and exclusion criteria, and the process we used to abstract relevant information from eligible articles and generate our evidence tables. We discuss our criteria for evaluating the quality of individual articles and synthesizing the evidence. Finally, we describe the peer review process.

Topic Development and Refinement

Efforts to improve the quality and value of health care increasingly emphasize a critical role for the meaningful use of CDSSs. The specific aim of clinical decision support is to provide patient-specific recommendations generated through a comparison of patient information with a knowledge resource.^{4,5} In general, CDSSs can enhance clinical effectiveness by improving the quality of care⁶ and patient outcomes by aiding health care providers in the decisionmaking process.^{7,8} However, in order for CDSSs to improve the quality of health care, there needs to be evidence-based and practice-based information that provides evidentiary knowledge applicable to the clinical setting and the clinician and patient interaction. As a form of health information technology, CDSSs can serve as an information tool to augment clinician decisionmaking with best practice guidelines and evidence at the point of care.

Within electronic KMSs and CDSSs, there is a continuum of decision support aides that have the goal of obtaining knowledge to inform a decision at the point of care or for a specific care situation.

Table 1 shows three types of decision support aides and how context-specific queries are processed by these aides to submit patient-specific information and retrieve patient-specific recommendations. This report examines each type of decision support aide presented in the table.

Table 1. Continuum of Decision Support

Types of decision support aides	Classic clinical decision support	Information retrieval tool	Knowledge resource
Example	Preventive care reminder	Infobutton	Epocrates
Process: Submit patient-specific information	Automated (computer)	Automated (computer)	Manual (human)
Process: Retrieve patient-specific recommendation	Automated (computer)	Manual (human)	Manual (human)

A **classic clinical decision support system** is defined as “any electronic system designed to aid directly in clinical decisionmaking, in which characteristics of individual patients are used to generate patient-specific assessments or recommendations that are then presented to clinicians for consideration.”⁹ An example of a classic CDSS is a preventive care reminder to remind the

clinician of a specific action. For this type of decision support, the processes to submit patient-specific information and retrieve patient-specific recommendations are automated and performed by a computer.

An **information retrieval tool** is defined as an electronic tool designed to aid clinicians in the search and retrieval of context-specific knowledge from information sources based on patient-specific information from a clinical information system to facilitate decisionmaking at the point of care or for a specific care situation. An example of an information retrieval tool is an infobutton embedded in a clinical information system, such as an EHR, that when selected provides context-specific links to various information sources. For this type of decision support, the process to submit patient-specific information is automated and performed by a computer, and the process to retrieve patient-specific recommendations is manually performed by a human.

A **knowledge resource** is defined as an electronic resource comprising distilled primary literature designed to facilitate decisionmaking at the point of care or for a specific care situation. Examples of knowledge resources include UpToDate, Epocrates®, and MDConsult. For this type of decision support, the processes to submit patient-specific information and retrieve patient-specific recommendations are manually performed by a human.

Several previous reviews^{5,9-15} have examined the effects of CDSSs. However, because different research inclusion and exclusion criteria were employed—which often included limitations for publication date, clinical setting (e.g., ambulatory, inpatient care), outcomes (e.g., clinical, process), or type/scope of CDSS (e.g., computerized reminders, computerized guidelines); narrowly-defined search strategies; exclusion of electronic information retrieval tools and knowledge resources; limited emphasis of what determines successful use and implementation of CDSSs and how those factors influence clinical and process outcomes—there are many unanswered questions regarding the impact of these tools in clinical practice and on patient outcomes. This report targets knowledge gaps from previous reviews as reflected in the key questions and evaluates the peer-reviewed research literature to provide information that will be useful for policymakers and decisionmakers engaged in using CDSSs and KMSs.

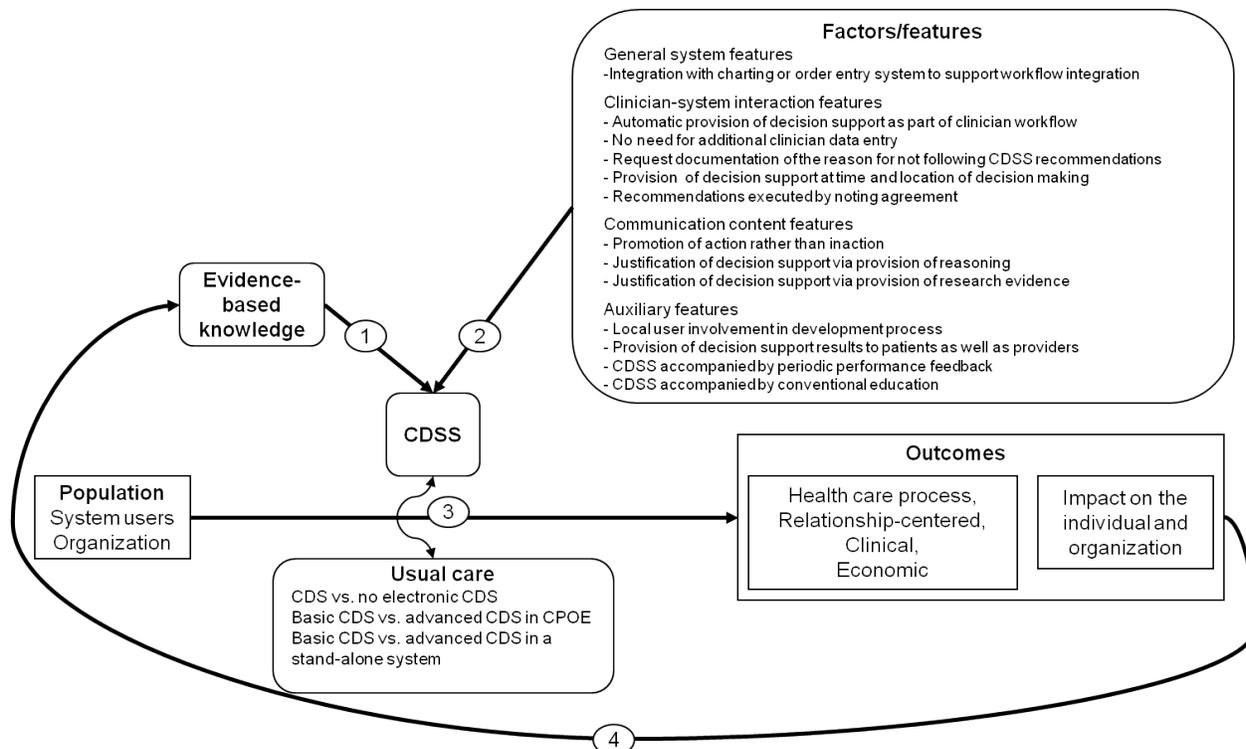
The key questions considered in this systematic review are:

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 - 4b. How a clinician's expertise/proficiency/informatics competency using the electronic knowledge management and CDSS affects patient outcomes (one type of measure)

Analytic Framework

The analytic framework (Figure 1) illustrates (1) how CDSS/KMS implementation and use is affected by evidence-based knowledge and contextual factors/features and (2) how interactions with CDSSs/KMSs by system users and health care organizations may result in outcomes such as changes in the individual, changes in the organization, and changes in health care quality.

Figure 1. Analytic Framework



Literature Search Strategy

Sources Searched

The comprehensive literature search included electronic searching of peer-reviewed literature databases. These databases included the Cumulative Index to Nursing and Allied Health Literature (CINAHL®), Cochrane Database, MEDLINE® accessed via PubMed®, PsycINFO®, and Web of Science®. Searches of these databases were supplemented with manual searching of reference lists contained in all included articles and in relevant review articles.

Screening for Inclusion and Exclusion

We developed a list of article inclusion and exclusion criteria for the key questions (Table 2) and modified the list after discussion with our TEP. We examined 14 factors/features of a successful CDSS identified in the Kawamoto et al. (2005)⁹ review as well as specific characteristics of those interventions (Table 3).

Table 2. Inclusion and Exclusion Criteria

Category	Criteria
Study population	KQs 1–4: <ul style="list-style-type: none"> • System user, defined as a health care provider (HCP) who interacts with the KMS or CDSS. Includes nurses, nurse practitioners, care managers, physician assistants, training MDs (residents, fellows), attending physicians or general practitioners, pharmacists. • Health care organization, defined as an organization that provides access to health care services delivered by medical and allied health professionals. Includes academic and community settings, clinics, practices, hospitals, long-term care facilities.
Study design	KQ 1: All study designs KQs 2-4: Randomized controlled trials (parallel group, crossover, cluster)
Factors/interventions	KQs 1–4: Implemented electronic KMS and CDSS (see Table 3)
Comparator	KQs 1–4: <ul style="list-style-type: none"> • CDSSs/KMSs are compared with no electronic CDSS/KMS • Basic CDSS is compared with advanced CDSS in computerized physician order entry (CPOE) or EHR • Basic CDSS is compared with advanced CDSS in a standalone system
Study outcomes	KQs 1-4: <ul style="list-style-type: none"> • Impact on clinical outcomes (length of stay, morbidity, mortality, measure of health-related quality of life, adverse events) • Impact on health care process outcomes (recommended preventive care, clinical study, or treatment was ordered/completed and adhered to) • Impact on workload, efficiency, and organization of health care delivery (number of patients seen, clinician workload, efficiency) • Impact on relationship-centered outcomes (patient satisfaction) • Impact on economic outcomes (cost and cost-effectiveness) • Impact on HCP use and implementation (acceptance, satisfaction, use, implementation)
Timing	No restrictions
Setting	No restrictions
Publication languages	English only

Category	Criteria
Admissible evidence (study design and other criteria)	KQs 1–4: <ul style="list-style-type: none"> • Study must report one or more outcomes of interest (see above criteria) • Study must report original data • Study must report sufficient details for data extraction and analysis • Intervention must be implemented in a real clinical setting • Intervention must be aimed at health care providers • Intervention must be used to aid decisionmaking at the point of care or for a specific care situation • Study must evaluate the effectiveness of KMS or CDSS
Exclusions	<ul style="list-style-type: none"> • Exclude studies of closed-loop systems that do not involve a provider • Exclude studies of systems that require mandatory compliance with the CDSS intervention, defined as when the clinician at the point of care is not given a choice on whether to follow the CDSS recommendations (compliance is mandated by the study protocol) • Exclude if the study evaluates only the performance of the system as opposed to the impact on clinical practice

Abbreviations: CDSS = clinical decision support system, CPOE = computerized physician order entry, EHR = electronic health record, HCP = health care provider, KMS = knowledge management system

Table 3. Factors and Features of CDSS Intervention Examined for KQ 2

<p>Source/origin of system Locally developed Commercially available</p> <p>Content Objective of the intervention:</p> <ul style="list-style-type: none"> ○ Diagnosis ○ Immunization ○ Pharmacotherapy ○ Lab test ordering ○ Chronic disease management ○ Initiating discussion with patient ○ Preventive care <p>Relationship to point of care:</p> <ul style="list-style-type: none"> ○ Synchronous ○ Asynchronous <p>Decision support Response requirement:</p> <ul style="list-style-type: none"> ○ Noncommittal acknowledgement ○ Justification for not complying ○ No response requirement ○ Mandatory response ○ NR (assume no response requirement) ○ NR (unclear whether response requirement) <p>Information delivery Delivery format:</p> <ul style="list-style-type: none"> ○ Online access ○ Integrated with CPOE or EHR ○ Standalone system ○ Paper-based <p>Delivery mode:</p> <ul style="list-style-type: none"> ○ System-initiated (“push”) ○ User-initiated (“pull”) 	<p>Contextual factors/features influencing the implementation and use of CDSSs/KMSs</p> <p>General system features Integration with charting or order entry system to support workflow integration</p> <p>Clinician-system interaction features Automatic provision of decision support as part of clinician workflow No need for additional clinician data entry Request documentation of the reason for not following CDSS recommendations Provision of decision support at time and location of decisionmaking Recommendations executed by noting agreement</p> <p>Communication content features Provision of a recommendation, not just an assessment Promotion of action rather than inaction Justification of decision support via provision of reasoning Justification of decision support via provision of research evidence</p> <p>Auxiliary features Local user involvement in development process Provision of decision support results to patients as well as providers CDSS accompanied by periodic performance feedback CDSS accompanied by conventional education</p>
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Process for Study Selection

Search strategies were specific to each database in order to retrieve the articles most relevant to the key questions. Our basic search strategy used the National Library of Medicine's Medical Subject Headings (MeSH) key word nomenclature developed for MEDLINE®, limited to articles published in English, and a manual search of retrieved articles and published reviews. Search terms and strategies were developed in consultation with a medical librarian. The exact search strings used in our strategy are given in Appendix A.

Using the prespecified inclusion and exclusion criteria, titles and abstracts were examined independently by three reviewers for potential relevance to the key questions. Articles included by any reviewer underwent full-text screening. After the independent abstract screening stage by a single reviewer, five percent of the abstracts were randomly selected using a random number generator for a rescreen by a second reviewer. At the full-text screening stage, two independent reviewers read each article to determine if it met eligibility criteria. At the full-text review stage, paired researchers independently reviewed the articles and indicated a decision to “include” or “exclude” the article for data abstraction. When the paired reviewers arrived at different decisions about whether to include or exclude an article, they reconciled the difference through a third-party arbitrator. Articles meeting our eligibility criteria were included for data abstraction.

Data Extraction and Data Management

Data from included reports were abstracted into evidence tables by one reviewer and overread by a second reviewer. Data elements abstracted included descriptors to assess applicability, quality elements, intervention details, and outcomes. Disagreements were resolved by consensus or by obtaining a third reviewer's opinion when consensus could not be reached. Appendix B contains a sample data abstraction form, and Appendix C describes the guidance used by the data abstractors.

The final evidence tables are intended to provide sufficient information so that readers can understand the study and determine its quality. Evidence tables for all included studies are presented in Appendix D, organized alphabetically by author.

Individual Study Quality Assessment

We employed internal and external quality-monitoring checks through every phase of the project to reduce bias, enhance consistency, and verify accuracy. Examples of internal monitoring procedures include three progressively stricter screening opportunities for each article (abstract screening, full-text screening, and data abstraction), involvement of three individuals in each data abstraction, and agreement of at least two investigators on all included studies.

The included studies were assessed on the basis of the quality of their reporting of relevant data. We evaluated the quality of individual studies using the approach described in AHRQ's *Methods Guide for Effectiveness and Comparative Effectiveness Reviews* (hereafter referred to as the *General Methods Guide*).¹⁶ To assess methodological quality, we employed the strategy to (1) apply predefined criteria for quality and critical appraisal and (2) arrive at a summary judgment of the study's quality. To indicate the summary judgment of the quality of the

individual studies, we used the summary ratings of Good, Fair, or Poor. Appendix C describes our quality assessment process.

To assess applicability, we identified specific issues that may limit the applicability of individual studies or a body of evidence as recommended in the *General Methods Guide*. Appendix C describes our applicability assessment process.

Data Synthesis

Given that many studies did not have the statistical power to determine the benefit for the outcomes relevant to this review (which were often not the primary outcomes evaluated by study investigators), we considered synthesis (meta-analysis) in an attempt to overcome the type II error. We considered groups of studies to be suitable candidates for a quantitative synthesis when we were able to identify at least four studies that assessed the same outcome that could be expressed using a common endpoint.

Estimates of parameters for the meta-analyses were combined using an empirical Bayes random-effects estimator as described by Hedges and Olkin (1985).¹⁷ This estimator has the property that it reduces to a fixed-effects estimator if no heterogeneity is present. The estimates are similar to those of DerSimonian and Laird (1986)¹⁸ but integrate over an empirical prior whereas the ones of DerSimonian and Laird are based on the point estimate of the random variation. The two methods generally give very similar results. Empirical Bayes estimates were computed using the FAST*PRO Software (Eddy and Hasselblad, 1992).¹⁹

Most endpoints were combined using odds ratios, especially when event rates that approached 1.0 were involved. However, the clinical endpoints such as morbidity, mortality, and length of stay were combined using relative risks. For these endpoints, the event rates were low, and some of the studies reported risk ratios instead of relative risks. Given the heterogeneity of CDSSs, and the lack of multiple studies evaluating the same CDSS, when studies were combined, pooling was performed without regard to the specific CDSS but rather comparing the CDSS versus control intervention.

Grading the Body of Evidence for Each Key Question

The strength of evidence for each key question was assessed using the approach described in the *General Methods Guide*.¹⁶ The evidence was evaluated using the four required domains: risk of bias, consistency, directness, and precision. Additionally, when appropriate, the studies were evaluated for coherence, dose-response association, residual confounding, strength of association (magnitude of effect), publication bias, and applicability. The strength of evidence was assigned an overall grade of High, Moderate, Low, or Insufficient.

Peer Review and Public Commentary

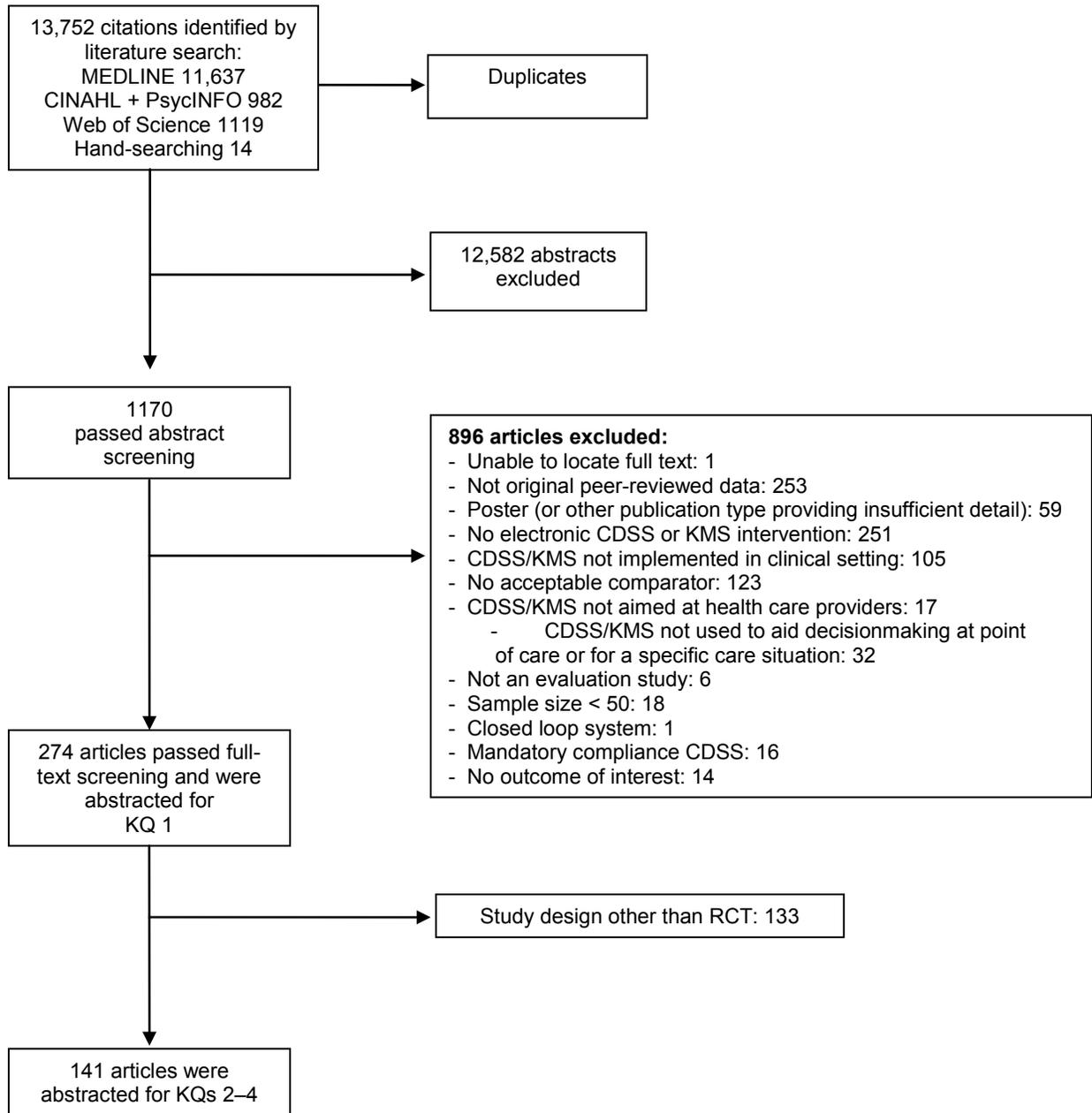
Our principal external quality-monitoring device is the peer review process. Nominations for peer reviewers were solicited from several sources, including the TEP and interested Federal agencies. The list of nominees was forwarded to AHRQ for vetting and approval. A list of reviewers submitting comments on this draft will be included in an Appendix to the final report.

Results

Literature Search Results

The flow of articles through the literature search and screening process is depicted in Figure 2. We identified 13,752 citations from all sources (after removing duplicates). After applying inclusion/exclusion criteria at the title-and-abstract level, 1170 full-text articles were retrieved and screened. Of these, 896 articles were excluded at full-text review, with 274 articles remaining for data abstraction. Of these, 274 articles were abstracted for Key Question 1 (representing 264 unique studies), and 141 articles (representing 131 unique studies) for Key Questions 2 through 4. Appendix E provides a complete listing of articles excluded at the full-text stage, with reasons for exclusion.

Figure 2. Literature Search Flow



Key Question 1

KQ 1: What evidence-based study designs can be used to determine the clinical effectiveness of CDSSs?

Key Points

- Clinical and health care process outcomes were frequently reported in all three study design types examined (randomized controlled trials [RCTs], quasi-experimental, and observational studies).
- Our analysis suggests that more RCTs measuring clinical outcomes are needed to evaluate the comparative effectiveness of CDSSs.
- When RCT studies are impractical to carry out, well-designed quasi-experimental and observational studies can be used to evaluate the clinical effectiveness of CDSSs.
- Ideal studies will measure clinical impact of CDSS implementation. In cases where the CDSS intervention is closely related to clinical outcomes, CDSS process outcomes may serve as appropriate surrogate measurements for the evaluation of clinical effectiveness.

Detailed Analysis

The objective assessment of a CDSS intervention's clinical effectiveness is important in understanding the value of that CDSS in a clinical setting. Selection of appropriate study design is critical for the proper evaluation of clinical performance in a system.²⁰ KQ 1 examines the use of different study designs in the existing CDSS evidence base in the evaluation of clinical effectiveness. Clinical effectiveness is simply defined as how well a particular intervention produces optimum processes and outcomes for patients. New CDSS interventions are invariably evaluated through a variety of direct, process-oriented measures that describe compliance with and acceptance of the system, but the clinical effectiveness of a CDSS is best evaluated with the direct measurement of patient-centric clinical outcomes following CDSS implementation.

While the responses to KQs 2, 3, and 4 considered CDSS implementation studies that only employed an RCT design, KQ 1 looked at RCTs as well as studies that employed other evaluation designs (quasi-experimental, observational) to assess their relative impacts on the measurement of CDSS clinical effectiveness.

Types of study designs. Two hundred sixty-four studies, published between 1976 and 2010, met basic inclusion criteria. We categorized these studies as one of 12 study designs, falling into 3 basic study types: RCT, quasi-experimental, and observational. Table 4 shows the selected study designs, descriptions of these study designs, and the number of included studies by design.

Table 4. Types of Evaluation Studies Included in This Review

Study type and design	Description	N included (% of total number of studies)
Randomized controlled trial		
Cluster	Groups of participants are randomized to the same intervention together	42 (16%)
Crossover	Participants receive one treatment and have outcomes measured, and then receive an alternative treatment and have outcomes measured again	3 (1%)
Parallel	Participants are randomly assigned to two or more groups, with at least one control group, and evaluated under identical or similar circumstances/timing	83 (31%)
Other	All other RCT studies	3 (1%)
		131 (49%) total RCT
Quasi-experimental		
Nonrandomized	Assignment to intervention(s) or control group is not randomized	12 (5%)
Before/after	Participants are evaluated before and after the introduction of an intervention	57 (22%)
Time series	Participants are evaluated at multiple time points before and after the intervention	24 (9%)
Other	All other quasi-experimental studies	6 (2%)
		99 (38%) total quasi-experimental
Observational		
Cohort	Participants with and without the intervention under study are followed and evaluated over time	21 (8%)
Case-control	Compares participants with condition of interest to participants without condition of interest who are otherwise similar	8 (3%)
Case series	Tracks participants with condition of interest, evaluating over time	3 (1%)
Other	All other observational studies	2 (1%)
		34 (13%) total observational
		264 total studies included

Categories of outcomes. To evaluate the use of specific study designs on the evaluation of CDSS clinical effectiveness, we abstracted outcome data from all included studies, compiling the relative prevalence of six key outcome categories in each of the three study designs. We considered direct measurement of clinical outcomes the means of measuring clinical effectiveness while evaluating KQ 1. Table 5 summarizes the outcome categories abstracted from the included studies and gives specific examples. Further details on the relative prevalence of outcome categories by study design are in Table F-1 of Appendix F.

Table 5. Outcome Categories Abstracted

Outcome Category	Examples
Clinical	Length of stay, morbidity, mortality, health-related quality of life, adverse events
Health care process	Adoption/implementation of CDSS-recommended preventive care/clinical study/treatment, patient adherence to CDSS recommendation, impact on user knowledge
Health care provider (HCP) workload, efficiency, and organization	Number of patients seen/unit time, clinician workload, efficiency
Relationship-centered	Patient satisfaction
Economic	Cost, cost-effectiveness

Outcome Category	Examples
Health care provider use and implementation	HCP acceptance, HCP satisfaction, HCP use and implementation of CDSS

Impact of study type on outcomes examined. Table 6 shows the prevalence of different outcome categories as they relate to basic study design. The total number of studies containing a particular outcome measure is given, followed by the percent of studies containing the outcome measure over the total number of studies within the given study design. All three study designs reported health care process measures most frequently, with 87% of all RCTs, 74% of all quasi-experimental, and 68% of all observational studies including at least one process-level outcome measure in their evaluation. The most frequent process measures reported in all three categories were outcomes that demonstrated compliance with CDSS-provided recommendations (Table F-2 in Appendix F). Other direct measures, such as the use of and satisfaction with CDSS by health care providers, were also frequently reported, especially in RCTs, with 35% of all RCTs containing outcomes related to CDSS use and implementation. Other outcomes related to CDSS use, including patient satisfaction (relationship-centered outcomes), efficiency (economic and workload outcomes), and patient well-being (clinical outcomes) were reported less frequently overall.

Table 6. Number of Studies Containing Outcome Measures by Study Type

Study type	Clinical	Health care process	HCP workload, efficiency, and organization	Relationship-centered	Economic	HCP use and implementation
RCT (N = 131)	33 (25%)	114(87%)	7 (5%)	7 (5%)	23 (18%)	46 (35%)
Quasi-experimental (N = 99)	31 (31%)	73 (74%)	23 (23%)	3 (3%)	16 (16%)	27 (27%)
Observational (N = 34)	13 (38%)	23 (68%)	1 (3%)	0 (0%)	3 (9%)	8 (24%)

Outcomes in RCTs. In RCT studies, health care process outcomes were reported most frequently (Table 6), with compliance with CDSS-recommended treatment the most commonly reported specific outcome (reported in 114 studies). HCP use and implementation was the second most commonly reported outcome category for RCT studies, with HCP use of CDSSs the most frequently occurring specific outcome in that category (reported in 46 studies). Clinical outcomes were reported moderately frequently in RCT studies, with morbidity the most commonly reported clinical outcome. A complete breakdown of outcomes by specific study type can be found in Table F-2 of Appendix F.

Outcomes in non-RCTs. Health care process outcomes were also the most frequently reported outcome type in non-RCT (quasi-experimental and observational) studies. Clinical outcomes were the second most commonly reported outcome for non-RCT studies, with mortality and morbidity being the most commonly reported clinical outcomes (Table F-2 of Appendix F).

Clinical outcomes. In Table 7, we further categorize the proportion of studies that measure clinical effectiveness into specific study type. This analysis demonstrates that 25% of all RCTs included clinical outcomes as at least one of their reported outcome measures, compared with 33% of non-RCT (quasi-experimental and observational studies) including clinical outcomes.

Table 7. Proportion of Specific Study Design Containing Clinical Outcomes

Study type and design	Studies including clinical outcomes (% of total)
RCT	
Cluster (N = 42)	10 (26%)
Cross-over (N = 3)	0 (0%)
Parallel (N = 83)	23 (28%)
Other (N = 3)	0 (0%)
Total RCT (N = 131)	33 (25%)
Quasi-Experimental	
Nonrandomized (N = 12)	6 (50%)
Before/After (N = 57)	19 (33%)
Time Series (N = 24)	5 (21%)
Other (N = 6)	1 (17%)
Total quasi-experimental (N = 99)	31 (31%)
Observational	
Cohort (N = 21)	10 (48%)
Case-control (N = 8)	2 (25%)
Case series (N = 3)	1 (33%)
Other (N = 2)	0 (0%)
Total observational (N = 34)	13 (38%)

Outcomes related to successful CDSS implementation. According to Davis' Technology Acceptance Model (TAM),²¹ users accept and use technology (such as a CDSS) based on two key factors: perceived usefulness and perceived ease-of-use. That is, a recommendation is likely to be successfully acted upon if HCPs perceive the CDSS intervention as useful in aiding critical decisionmaking at the point of care. HCPs appear most comfortable considering recommendations when CDSS interventions provide adequate information toward decisive action in a timely manner. This finding seems to be consistent with studies reporting HCP acceptance and satisfaction of using. Such studies are also likely to report health care process and/or clinical outcomes. In our studies, 18 of all articles reporting HCP use and implementation outcomes (22%) also reported clinical outcomes. Similarly, 54 of all articles reporting HCP use and implementation outcomes (67%) also reported health care process outcomes.

Discussion and Future Research

In the current body of literature, most CDSS implementation studies do not examine clinical outcomes, instead focusing on the more immediately measurable process-oriented outcomes. Of the included studies that examined clinical outcomes, very few are RCT studies. These trends can likely be attributed to the relative difficulty of implementing RCT studies in real clinical settings as well as the logistical issues involved in measuring the indirect clinical impact of CDSS interventions.

Challenges in conducting RCT studies in real clinical settings. One of the challenges in conducting RCT studies in real clinical settings is the enforcement of true randomization. Clinicians frequently consult with one another about treatment options or medications, especially when they change their shift. Also, clinicians may be tempted to share their experiences of using CDSSs with their colleagues and inadvertently influence their attitude toward the use of CDSS.²⁰ Therefore, blinding clinicians to CDSS interventions within the same ward or hospital setting is usually difficult to control. We found 42 of the included RCTs (16%) conducted cluster RCTs,

where groups of patients and clinicians are randomized rather than individuals, in order to protect against contamination across trial groups.

Large randomized trials related to the use of CDSSs tend to occur most often in well-established institutions such as Brigham and Women's Hospital/Partners Health Care/Massachusetts General Hospital in Boston, Regenstrief Institute in Indianapolis, and LDS Hospital/Intermountain Healthcare in Utah. This trend may be related to factors common at these research-intensive institutions, such as the availability of well-defined electronic medical records system, infrastructure supporting the implementation of a CDSS, and a clinician culture that supports the exploration of CDSS adoption as part of their clinical practice. This may well explain the higher adoption rate of CDSSs among these institutions, which subsequently provided them with the opportunity to conduct more randomized trials to evaluate the clinical impact of CDSS interventions.

Challenges in measuring clinical outcomes. All three study types reported a much higher prevalence of process-oriented outcomes (outcomes directly related to the implementation of, and compliance to, the CDSS intervention being evaluated) than of clinical outcomes (patient-centric outcomes often separated from the actual CDSS temporally and practically). This difference is likely due to the fact that, regardless of design, process outcomes (for example, compliance with CDSS-recommended drug dosage) are generally easier and faster to measure and evaluate than clinical outcomes (length of stay, morbidity). The impact of CDSSs on clinical outcomes related to the CDSS implementation must often necessarily occur for several days to several months after the initial implementation, and measuring such impacts often requires costly and cumbersome followup, delaying evaluation of the CDSS. In situations where the CDSS process and the clinical outcome are closely aligned (for example, a CDSS providing drug-dosage calculations based on patient parameters), measuring the process may serve as an acceptable surrogate for a clinical outcome. In cases where the CDSS process is not closely related to clinical effectiveness (for example, systems that recommend treatment plans based on evidence-based standards), clinical outcomes will need to be measured directly to understand the true effects of CDSSs.

Given the challenges inherent both in implementing RCTs and in measuring the clinical impact of interventions in real clinical settings, the relative lack of studies that report on RCTs assessing a clinical outcome is not surprising. Although studies that both follow RCT design and directly measure patient-centered clinical outcomes would be ideal, such studies are clearly not always feasible—logistically or economically. Whether studies should dedicate presumably limited resources either to adhering to RCT design or to measuring clinical outcomes depends on the nature of the CDSS being evaluated. If the CDSS itself is closely related to clinical outcomes (as discussed above), then process-oriented outcomes are likely sufficient, and resources should be dedicated to the execution of RCT studies. If, however, the CDSS process is linked only indirectly to clinical effectiveness, then process outcomes will not be sufficient. In these cases, measuring clinical outcomes directly becomes necessary to evaluate clinical effectiveness. When limited resources will necessarily be devoted to the time and effort required to measure clinical outcomes, quasi-experimental and observational studies can be effective choices for study design, provided they are conducted as rigorously as possible.

Key Question 2

KQ 2: What contextual factors/features influence the implementation and use of electronic knowledge management and CDSSs?

Key Points

- A meta-analysis of included studies confirmed the three key factors/features identified in the review by Kawamoto et al. (2005)⁹ that were strongly associated with a successful CDSS that improved clinical practice, although we were unable to distinguish the impact of a specific factor/feature. These factors were significant across all three endpoints assessed: (1) adherence to performing preventive care, (2) adherence to performing a clinical study, and (3) adherence to prescribing a treatment. The three features are:
 - Automatic provision of decision support as part of clinician workflow
 - Provision of decision support at time and location of decisionmaking
 - Provision of a recommendation, not just an assessment
- The meta-analysis also identified four additional factors/features that were correlated with the success of a CDSS across all three endpoints:
 - Integration with charting or order entry system to support workflow integration
 - Promotion of action rather than inaction
 - No need for additional clinician data entry
 - Local user involvement in the development process
- Additionally, four factors/features were found to correlate with a successful CDSS across two of the three endpoints evaluated:
 - Justification of decision support via provision of reasoning
 - Justification of decision support via provision of research evidence
 - Provision of decision support results to patients as well as providers
 - A CDSS accompanied by periodic performance feedback
- One factor/feature was significant for only one endpoint (adherence to performing a clinical study, only two studies in the group): recommendations executed by noting agreement; and one factor/feature was not significant across any of the three endpoints: request documentation of the reason for not following CDSS recommendations.

Detailed Analysis

This section of the evidence report examines the factors/features that influence the implementation and use of CDSSs/KMSs. We will present findings from the literature search on the generalized factors/features of successful CDSSs and then the factors/features of CDSSs according to outcomes.

Within this body of evidence, we examined the inclusion of 14 factors/features in electronic CDSSs that were identified from a previous review⁹ and from suggestions from the TEP that were viewed as potentially important in determining a CDSS's success in improving clinical practice. To further assess the impact of various factors/features on the success of a CDSS, we used meta-analysis to analyze the 14 most common features across the three outcomes for which we had the most studies—adherence to performing a preventive care service, adherence to performing a clinical study, and adherence to prescribing a treatment. The majority of the 131 included studies described CDSSs that included the following five factors/features:

1. Provision of decision support at the time and location of decisionmaking (n = 111; 85%)
2. Automatic provision of decision support as part of clinician workflow (n = 103; 79%)
3. Provision of a recommendation, not just an assessment (n = 100; 76%)
4. Integration with charting or order entry to support workflow integration (n = 84; 64%)
5. No need for additional clinician data entry (n = 74; 56%)

Of the 14 electronic factors/features that we identified, three had been shown in a previous review to be strongly associated with improving clinical practice: (1) automatic provision of decision support as part of clinician workflow, (2) provision of decision support at time and location of decisionmaking, and (3) provision of a recommendation, not just an assessment. From the meta-analysis conducted for this review, we identified four additional factors/features that correlated with a successful CDSS implementation: (4) the incorporation with charting or order entry system to support workflow integration, (5) the promotion of action rather than inaction, (6) no need for additional clinician data entry, and (7) local user involvement in the development process. We observed that 15 (11.5%) of our studies included all 7 of those factors. One hundred fifteen (87.8%) of the 131 studies included some combination of the 7 factors—32 studies (24.4%) included 6 factors; 26 studies (19.8%) included 5 factors; 20 studies (15.3%) included 4 factors; 20 studies (15.3%) included 3 factors; 10 studies included 2 factors; 7 studies included 1 factor; and 1 study did not include any of those factors.

The following section will present findings from the literature search on three key categories of outcomes (clinical, process, use) related to the implementation and use of CDSSs/KMSs. Within each category, we present general observations of the factors/features that the majority of systems possessed, followed by an examination of the factors/features of the CDSSs for each outcome.

Process Outcomes

General observations. Forty-three studies that evaluated the implementation and use of CDSSs on process outcomes and reported a significant improvement in the appropriate ordering/completion of preventive care services, clinical studies, and treatment consistently had the seven key factors/features correlated with a successful CDSS, three previously reported in 2005⁹ and four identified through meta-analysis for the current report.

Previously identified factors/features and the relevant included studies were:

1. Automatic provision of decision support as part of clinician workflow²²⁻⁵⁷
2. Provision of decision support at time and location of decisionmaking^{23-32,34-36,38-49,51,52,55-63}
3. Provision of a recommendation, not just an assessment^{23-29,31,32,34-36,38-49,51,52,55-59,61-63}

Newly identified factors/features and the relevant included studies were:

4. Integration with charting or order entry system^{23-29,31-33,35,36,41-47,50-54,56-58,64}
5. No need for additional data entry^{23,25-29,31-37,41-43,45-48,50-54,56,57,59}
6. Promotion of action rather than inaction^{23,24,26,27,31,32,35-37,39,42-47,51,52,58-61,64}
7. Local user involvement in the development process^{24-28,35-37,39,43-46,48,56,57,60,61,63,65}

Factors/features of the 43 studies that evaluated CDSSs on process outcomes across settings.

Twenty studies (46.5%) evaluated in the *academic setting* consistently had the three key factors/features previously associated with a successful CDSS.^{23,26,28,36-38,40-47,50,53,57,60,63,66,67}

Thirteen studies (30.2%) evaluated in the *community setting* consistently had the three previously identified key factors/features.^{27,29-32,35,39,49,51,56,58,59,61,62} Four studies (9.3%) evaluated in both

academic and community settings consistently had two of the previously identified key factors/features (automatic provision of decision support as part of clinician workflow and provision of decision support at time and location of decisionmaking) and one newly identified key factor/feature (integration with charting or order entry system to support workflow).^{24,33,55,64}

Thirty-one studies (72.1%) were conducted in the *ambulatory setting* and consistently had the three previously identified key factors/features.^{24,25,27,29-33,35,37-42,45,46,50-56,58-65} Seven studies

(16.3%) conducted in the *hospital setting* consistently had the three previously identified key factors/features and three newly identified key factors/features (integration with charting or order entry system, no need for additional data entry, and promotion of action rather than inaction).^{23,26,36,43,44,47,57} Three studies (7%) conducted in the *emergency department* consistently

had the provision of decision support at time and location of decisionmaking.^{48,49,66,67} Twenty-eight CDSS interventions (65.1%) implemented in *locally developed systems* consistently had the three previously identified key factors/features.^{23-27,34,36-42,44,45,47-49,52-54,57,59-64} Nine CDSS

interventions (20.9%) implemented in *commercially developed systems* consistently had the three previously identified key factors/features and two newly identified key factors/features (integration with charting or order entry system and no need for additional data entry).^{28,31-33,35,43,51,56,58,65}

Preventive care adherence. We identified 40 of the 131 eligible studies (30.5%) that evaluated adherence to order/complete a preventive care service as an outcome of CDSS implementation and use. These studies are summarized in Table G-1 of Appendix G. We conducted a meta-analysis that focused on CDSS studies in which at least one outcome was related to ordering or completing preventive care services. Of the 40 studies, 22 included data with a common dichotomous endpoint and were included in the meta-analysis.^{4,25,26,30-32,36,37,41,51,55,58-60,62,65,68-74}

Across the studies, we examined the specific factors/features of each CDSS, and those odds ratios were combined using an empirical Bayes random-effects estimator. Findings from this analysis are listed in Table 8.

Table 8. Random Effects Empirical Bayes Estimates of the Odds Ratio for Preventive Care Adherence

Factor	Number of studies	Estimated odds ratio	95 % confidence limits
All studies	22	1.37	1.16 to 1.62
Integration with charting or order entry system to support workflow integration	12	1.48	1.06 to 2.06
Automatic provision of decision support as part of clinician workflow	16	1.38	1.13 to 1.68
No need for additional clinician data entry	15	1.41	1.08 to 1.84
Request documentation of the reason for not following CDSS recommendations	1	NA	NA
Provision of decision support at time and location of decisionmaking	20	1.39	1.17 to 1.65
Recommendations executed by noting agreement	5	1.27	0.97 to 1.66
Provision of a recommendation, not just an assessment	18	1.41	1.11 to 1.80
Promotion of action rather than inaction	15	1.28	1.08 to 1.52
Justification of decision support via provision of reasoning	7	1.58	1.22 to 2.06
Justification of decision support via provision of research evidence	5	1.64	1.02 to 2.65
Local user involvement in development process	10	1.49	1.13 to 1.95
Provision of decision support results to patients as well as providers	4	1.18	1.01 to 1.38
CDSS accompanied by periodic performance feedback	2	0.98	0.87 to 1.11
CDSS accompanied by conventional education	5	1.40	0.95 to 2.06

This analysis confirmed that the three previously identified key factors/features critical for CDSS success had a statistically significant impact on promoting adherence to preventive care outcomes: automatic provision of decision support as part of clinician workflow (OR 1.38; 95% CI 1.13 to 1.68), provision of decision support at time and location of decisionmaking (OR 1.39; 95% CI 1.17 to 1.65), and provision of a recommendation, not just an assessment (OR 1.41; 95% CI 1.11 to 1.80). The analysis also supported the four newly identified factors/features universally associated with CDSS success: integration with charting or order entry system to support workflow integration (OR 1.48; 95% CI 1.06 to 2.06), no need for additional clinician data entry (OR 1.41; 95% CI 1.08 to 1.84), promotion of action rather than inaction (OR 1.28; 95% CI 1.08 to 1.52), and local user involvement in development process (OR 1.49; 95% CI 1.13 to 1.95).

Finally, this analysis discovered three new factors/features that also were associated with a successful CDSS: justification of decision support via provision reasoning (OR 1.58; 95% CI 1.22 to 2.06), justification of decision support via provision of research evidence (OR 1.64; 95% CI 1.02 to 2.65), and provision of decision support results to patients as well as providers (OR 1.18; 95% CI 1.01 to 1.38). Unfortunately, because many of the studies included more than one factor/feature, and because the studies did not specifically evaluate whether the systems with and

without an individual factor differed in terms of their impact on the outcome of interest, it is difficult to determine the importance of individual factors/features.

Thirteen studies reported a significant improvement in preventive care adherence, and those CDSSs included the following factors/features:

- Nine included automatic provision of decision support as part of clinician workflow^{25,26,30,36,37,41,51,55,58}
- Twelve included provision of decision support at time and location of decisionmaking^{25,26,30,36,37,41,51,55,58-60,65}
- Nine included provision of a recommendation, not just an assessment^{25,26,36,41,51,55,58,59,62}
- Six included integration with charting or order entry system^{25,26,36,41,51,58}
- Seven included no need for additional data entry^{25,26,36,37,41,51,59}
- One included request documentation of the reason for not following the CDSS recommendations³⁷
- Three included recommendations executed by noting agreement^{26,37,51}
- Seven included promotion of action rather than inaction^{26,36,37,51,58-60}
- Six included justification of decision support via provision of reasoning^{25,26,36,37,51,60}
- Three included justification of decision support via provision of research evidence^{25,36,60}
- Six included local user involvement in development process^{25,26,36,37,60,65}
- One included provision of decision support results to patients as well as providers⁵⁹
- Two included a CDSS accompanied by conventional education^{25,55}

Clinical study adherence. We identified 24 of the 131 eligible studies (18.3%) that evaluated adherence to order/complete a clinical study as an outcome of CDSS implementation and use. These studies are summarized in Table G-2 of Appendix G. We conducted a meta-analysis that focused on CDSS studies in which at least one outcome was related to ordering or completing clinical studies. Of the 24 studies, 17 included data with a common dichotomous endpoint and were included in the meta-analysis.^{23,24,38,42,45,46,48-50,52,63,75-80} Across the studies, we examined the specific factors/features of each CDSS, and those odds ratios were combined using an empirical Bayes random-effects estimator. Findings from this analysis are listed in Table 9.

Table 9. Random Effects Empirical Bayes Estimates of the Odds Ratio for Clinical Study Adherence

Factor	Number of studies	Estimated odds ratio	95 % confidence limits
All studies	17	2.04	1.49 to 2.81
Integration with charting or order entry system to support workflow integration	7	1.67	1.30 to 2.15
Automatic provision of decision support as part of clinician workflow	13	2.05	1.53 to 2.73
No need for additional clinician data entry	9	1.71	1.25 to 2.35
Request documentation of the reason for not following CDSS recommendations	2	1.65	0.78 to 3.47
Provision of decision support at time and location of decisionmaking	13	2.09	1.42 to 3.06
Recommendations executed by noting agreement	2	1.43	1.22 to 1.67
Provision of a recommendation, not just an assessment	13	2.49	1.70 to 3.63
Promotion of action rather than inaction	9	1.64	1.25 to 2.16
Justification of decision support via provision of reasoning	4	1.59	0.92 to 2.77

Factor	Number of studies	Estimated odds ratio	95 % confidence limits
Justification of decision support via provision of research evidence	5	3.00	1.22 to 7.39
Local user involvement in development process	10	1.91	1.12 to 3.04
Provision of decision support results to patients as well as providers	4	1.80	1.15 to 2.83
CDSS accompanied by periodic performance feedback	2	4.63	1.24 to 17.22
CDSS accompanied by conventional education	7	1.52	1.02 to 2.27

This analysis confirmed that CDSSs that include the three previously identified key factors/features that are critical for CDSS success had a statistically significant impact on clinical study adherence outcomes: automatic provision of decision support as part of clinician workflow (OR 2.05; 95% CI 1.53 to 2.73), provision of decision support at time and location of decisionmaking (OR 2.09; 95% CI 1.42 to 3.06), and provision of a recommendation, not just an assessment (OR 2.49; 95% CI 1.70 to 3.63). The analysis also supported the four newly identified factors/features universally associated with CDSS success: integration with charting or order entry system to support workflow integration (OR 1.67; 95% CI 1.30 to 2.15), no need for additional data entry (OR 1.71; 95% CI 1.25 to 2.35), promotion of action rather than inaction (OR 1.64; 95% CI 1.25 to 2.16), and local user involvement in development process (OR 1.91; 95% CI 1.12 to 3.04).

Finally, this analysis discovered five new factors/features that were also associated with a successful CDSS: recommendations executed by noting agreement (OR 1.43; 95% CI 1.22 to 1.67), justification of decision support via provision of research evidence (OR 3.00; 95% CI 1.22 to 7.39), provision of decision support results to patients as well as providers (OR 1.80; 95% CI 1.15 to 2.83), CDSSs accompanied by periodic performance feedback (OR 4.63; 95% CI 1.24 to 17.22), and CDSSs accompanied by conventional education (OR 1.52; 95% CI 1.02 to 2.227). Unfortunately, because many of the studies included more than one factor/feature and because the studies did not specifically evaluate whether the systems with and without an individual factor differed in terms of their impact on the outcome of interest, it is difficult to determine the importance of individual factors/features.

Eleven studies reported a significant improvement in clinical study adherence, and those CDSS interventions included the following factors/features:

- Ten included automatic provision of decision support as part of clinician workflow^{23,24,38,42,45,46,48-50,52}
- Eight included provision of decision support at time and location of decisionmaking^{23,24,42,48-50,52,63}
- Ten included provision of a recommendation, not just an assessment^{23,24,38,42,45,46,48-50,52,63}
- Seven included integration with charting or order entry system^{23,24,42,45,46,50,52}
- Seven included no need for additional data entry^{23,42,45,46,48,50,52}
- One included request documentation of the reason for not following the CDSS recommendations²³
- Two included recommendations executed by noting agreement^{45,46}

- Six included promotion of action rather than inaction^{23,24,42,45,46,52}
- Two included justification of decision support via provision of reasoning^{24,52}
- Three included justification of decision support via provision of research evidence^{24,38,63}

Treatment adherence. We identified 61 of the 131 eligible studies (46.6%) that evaluated treatment adherence as an outcome of CDSS implementation and use. These studies are summarized in Table G-3 of Appendix G. We conducted a meta-analysis that focused on CDSS studies in which at least one outcome was related to ordering treatments or prescribing therapies. Of the 61 studies, 39 studies included data with a common dichotomous endpoint and were included in the meta-analysis.^{24,27-29,31-35,38-40,43,44,47,53,54,56-58,61,62,64,66-68,73,79,81-93} Across the studies, we examined the specific factors/features of each CDSS, and those odds ratios were combined using an empirical Bayes random-effects estimator. Findings from this analysis are listed in Table 10.

Table 10. Random Effects Empirical Bayes Estimates of the Odds Ratio for Treatment Adherence

Factor	Number of studies	Estimated odds ratio	95 % confidence limits
All studies	39	1.55	1.28 to1.89
Integration with charting or order entry system to support workflow integration	30	1.61	1.28 to2.03
Automatic provision of decision support as part of clinician workflow	33	1.55	1.24 to1.95
No need for additional clinician data entry	25	1.71	1.30 to2.26
Request documentation of the reason for not following CDSS recommendations	3	3.20	0.60 to17.02
Provision of decision support at time and location of decisionmaking	31	1.72	1.37 to2.14
Recommendations executed by noting agreement	4	1.58	0.97 to2.58
Provision of a recommendation, not just an assessment	30	1.61	1.25 to2.06
Promotion of action rather than inaction	18	1.56	1.18 to2.07
Justification of decision support via provision of reasoning	10	1.41	1.04 to1.91
Justification of decision support via provision of research evidence	13	1.58	0.98 to2.54
Local user involvement in development process	18	1.98	1.40 to2.78
Provision of decision support results to patients as well as providers	5	2.14	0.98 to4.66
CDSS accompanied by periodic performance feedback	2	1.53	1.22 to1.90
CDSS accompanied by conventional education	7	1.27	0.93 to1.73

This analysis confirmed that CDSSs that include the three previously identified key factors/features critical for CDSS success had a statistically significant impact on treatment adherence outcomes: automatic provision of decision support as part of clinician workflow (OR 1.55; 95% CI 1.24 to 1.95), provision of decision support at time and location of decisionmaking (OR 1.72; 95% CI 1.37 to 2.14), and provision of a recommendation, not just an assessment (OR 1.61; 95% CI 1.25 to 2.06). The analysis also supported the four newly identified factors/features universally associated with CDSS success: integration with charting or order entry system to support workflow integration (OR 1.55; 95% CI 1.28 to 2.03), no need for additional data entry

(OR 1.71; 95% CI 1.30, 2.26), promotion of action rather than inaction (OR 1.56; 95% CI 1.18 to 2.07), and local user involvement in development process (OR 1.98; 95% CI 1.40 to 2.78).

Finally, this analysis also identified two factors/features that were significant, namely, justification of decision support via provision reasoning (OR 1.41; 95% CI 1.04 to 1.91) and CDSSs accompanied by periodic performance feedback (OR 1.53; 95% CI 1.22 to 1.90). Unfortunately, because many of the studies included more than one factor/feature and because the studies did not specifically evaluate whether the systems with and without an individual factor differed in terms of their impact on the outcome of interest, it is difficult to determine the importance of individual factors/features.

Twenty studies reported a significant improvement in treatment adherence, and those CDSSs included the following factors/features:

- Seventeen included automatic provision of decision support as part of clinician workflow^{24,27-29,31-35,39,40,43,44,47,53,54,56,57}
- Nineteen included provision of decision support at time and location of decisionmaking^{24,27-29,31-35,39,43,44,47,53,54,56,57,61,64,66,67}
- Fifteen included provision of a recommendation, not just an assessment^{24,27-29,31,32,34,35,39,40,43,44,47,56,57,61}
- Sixteen included integration with charting or order entry system^{24,27-29,31-33,35,43,44,47,53,54,56,57,64}
- Thirteen included no need for additional data entry^{27-29,31-35,43,47,53,54,56,57}
- One included request documentation of the reason for not following the CDSS recommendations⁶¹
- Two included recommendations executed by noting agreement^{35,53}
- Nine included promotion of action rather than inaction^{24,27,31,32,35,43,44,47,61,64}
- Four included justification of decision support via provision of reasoning^{24,61,64,66,67}
- Three included justification of decision support via provision of research evidence^{24,27,61}
- Nine included local user involvement in the development process^{24,28,35,39,43,44,56,57,61}
- Three included provision of decision support results to patients as well as providers^{27,31,32,39}
- One included CDSSs accompanied by periodic performance feedback^{31,32}
- Three included CDSSs accompanied by conventional education^{24,29,31,32}

Clinical Outcomes

General observations. The six studies that evaluated the implementation and use of CDSSs on clinical outcomes and reported a significant reduction in mortality, morbidity, adverse events, and length of stay consistently had two of the factors/features identified in the Kawamoto et al. (2005)⁹ review:

1. Automatic provision of decision support as part of clinician workflow^{36,44,81,90,94}
2. Provision of a recommendation, not just an assessment^{36,44,81,90,95}

Factors/features of the six studies that evaluated CDSSs on clinical outcomes across settings. Four studies (66.7%) evaluated in the *academic setting* consistently had the three key factors/features previously associated with a successful CDSS and two newly identified factors/features: promotion of action rather than inaction and local user involvement in the development process.^{36,44,94,95} Four studies (66.7%) conducted in the *ambulatory setting* consistently had two of the previously identified key factors/features: automatic provision of decision support as part of clinician workflow and provision of a recommendation, not just an assessment.^{81,90,94,95} Two studies (33.3%) evaluated in the *hospital setting* consistently had the three previously identified key factors/features and three newly identified factors/features: integration with charting or order entry system, promotion of action rather than inaction, and local user involvement in development process.^{36,44}

Mortality. We identified 6 of the 131 eligible studies (4.6%) that evaluated mortality as an outcome of CDSS implementation and use. These studies are summarized in Table G-4 of Appendix G. The studies consistently had five of the seven factors/features associated with a successful CDSS: integration with charting or order entry system; automatic provision of decision support as part of clinician workflow; no need for additional data entry; provision of a recommendation, not just an assessment; and promotion of action rather than inaction.

Two of the six studies reported a significant reduction in mortality.^{81,90} Ansari et al. (2003)⁸¹ assessed treatment reminders to improve the appropriate use of beta blockers for patients with congestive heart failure in 169 patients for 1 year and found a significant reduction in mortality (RR 0.1182; 95% CI 0.01598 to 0.8744). Roumie et al. (2006)⁹⁰ evaluated guideline-based recommendations for patients with uncontrolled hypertension in 1341 patients for 6 months and reported that the intervention groups had a significantly lower mortality rate than the control group (RR 0.2356; 95% CI 0.06311 to 0.8794). Those CDSSs included the following factors/features:

- Automatic provision of decision support as part of clinician workflow^{81,90}
- Provision of decision support at time and location of decisionmaking⁸¹
- Provision of a recommendation, not just an assessment^{81,90}
- Integration with charting or order entry system^{81,90}
- No need for additional data entry^{81,90}
- Promotion of action rather than inaction⁸¹
- A CDSS accompanied by conventional education⁸¹

Morbidity. We identified 25 of the 131 eligible studies (19.1%) that evaluated morbidity as an outcome of CDSS implementation and use. These studies are summarized in Table G-5 of Appendix G. The studies consistently had three of the seven factors/features associated with a

successful CDSS: automatic provision of decision support as part of clinician workflow; provision of decision support at time and location of decisionmaking; and provision of a recommendation, not just an assessment; and provision of a recommendation, not just an assessment.

Two of the 25 studies reported a significant reduction in morbidity.^{36,94} Kucher et al. (2005)³⁶ evaluated alerts that identified patients at risk for developing deep vein thrombosis (DVT) among 2506 high-risk hospitalized patients over 40 months (RR 0.6043; 95% CI 0.4341 to 0.8412). McDonald et al. (1984)⁹⁴ investigated reminders regarding preventive care services to improve provider adherence in 12,467 patients for 2 years and found that intervention patients had significantly fewer hospitalizations and emergency department visits than control patients (RR 0.6889; 95% CI 0.5233 to 0.9069). These two CDSSs included the following factors/features:

- Automatic provision of decision support as part of clinician workflow^{36,94}
- Provision of decision support at time and location of decisionmaking^{36,94}
- Provision of a recommendation, not just an assessment³⁶
- Integration with charting or order entry system³⁶
- No need for additional data entry³⁶
- Promotion of action rather than inaction³⁶
- Justification of decision support via provision of reasoning^{36,94}
- Justification of decision support via research evidence^{36,94}
- Local user involvement in development process^{36,94}

Adverse events. We identified 6 of the 131 eligible studies (4.6%) that evaluated adverse events as an outcome of CDSS implementation and use. These studies are summarized in Table G-6 of Appendix G. The studies consistently had four of the seven factors/features associated with a successful CDSS: integration with charting or order entry system; automatic provision of decision support as part of clinician workflow; provision of a recommendation, not just an assessment; and local user involvement in the development process.

One of the six studies found a significant reduction in adverse events.⁹⁵ Terrell et al. (2009) evaluated prescribing alerts that targeted potentially inappropriately prescribed medications for elderly emergency department patients in 5162 patient visits for 2.5 years and reported that there were significantly fewer inappropriate prescriptions in the intervention group compared to the control group (RR 0.6296; 95% CI 0.4672 to 0.8486). That system included three key factors/features associated with CDSS success: provision of decision support at time and location of decisionmaking, promotion of action rather than inaction, and local user involvement in the development process.

Length of stay. We identified 5 of the 131 eligible studies (3.8%) that evaluated length of stay as an outcome of CDSS implementation and use. These studies are summarized in Table G-7 of Appendix G. The studies consistently had four key factors/features associated with CDSS success: automatic provision of decision support; provision of decision support at time and location of decisionmaking; provision of a recommendation, not just an assessment; and local user involvement in the development process.

One of the five studies found a significant reduction in length of stay.⁴⁴ Paul et al. (2006) evaluated a standalone system that focused on decreasing inappropriate antimicrobial use by recommending the three “best” antibiotic regimens in 2326 patients over 7 months and reported

that the intervention group had significantly lower length of stay than the control group (RR 0.9082; 95% CI 0.8392 to 0.9828). That system included six key factors/features associated with successful CDSS: integration with charting or other entry system; automatic provision of decision support; provision of decision support at time and location of decisionmaking; provision of a recommendation, not just an assessment; promotion of action rather than inaction; and local user involvement in the development process.

HCP Use

We identified 15 of the 131 eligible studies (11.5%) that evaluated provider use as an outcome of CDSS implementation. These studies are summarized in Table G-8 of Appendix G. Fifteen studies evaluated the implementation and use of CDSS on HCP use, and those studies consistently had two of the three previously identified key factors/features: provision of decision support at time and location of decisionmaking and provision of a recommendation, not just an assessment.^{4,29,64,96-109} Eight studies (53.3%) evaluated in the *community setting* consistently had two of the three previously identified key factors/features: provision of decision support at time and location of decisionmaking and provision of a recommendation, just an assessment.^{4,29,98,99,101-103,106,109} Eleven CDSS interventions (73.3%) implemented in *locally developed systems* consistently had two of the three previously identified key factors/features: provision of decision support at time and location of decisionmaking and provision of a recommendation, not just an assessment.^{64,96-98,101-109} Three CDSS interventions (20%) implemented in *commercially developed systems* consistently had one of the three previously identified key factors/features: the provision of decision support at time and location of decisionmaking.^{4,99,100}

Key Question 3

KQ 3: What is the impact of introducing electronic knowledge management and CDSSs?

- a. Changes in the organization of health care delivery
- b. Changes in the workload and efficiency for the user
- c. Changes in process and clinical outcomes

Key Points

- There is strong evidence from the ambulatory setting that electronic CDSSs used at the point of care enhance health care process outcomes.
- We found that over 88% of the studies measured some type of health care process outcomes whereas only 28% of the studies assessed a clinical outcome, thus demonstrating that a gap exists in translating process outcomes into improvements in clinical outcomes such as mortality, morbidity, length of stay, and adverse events.
- The evidence is scarce that these systems increase the value of care while decreasing costs.
- There is limited evidence examining the impact of decision support tools on provider attitudes, workload, and efficiency.

- Longer evaluation periods and larger sample sizes are needed to better assess the impact of CDSSs on outcomes.
- More emphasis on the impact of CDSSs on providers, efficiency, and workload is needed to better understand how provider interaction and attitudes impact the quality of care delivered.

Detailed Analysis

Highlighted papers. Given the size and complexity of the published evidence, throughout our analysis of KQ 3, we examined a set of 10 high-quality, recently published papers in which the CDSS interventions were thoroughly described. Discussion of these 10 papers and the impact of the CDSSs on the outcomes of interest were used to help orient the reader to the broader evidence base and to inform the observations about the larger group of studies that evaluated each outcome category.^{24,28,52,77,83,95-97,100,110,111}

Six key categories of outcomes. From our examination of the impact of CDSSs and KMSs on clinical effectiveness and improved quality of care and patient outcomes, we present findings from the literature on six key categories of outcomes. The outcomes are discussed according to the strength of the best evidence generated from medium- to large-size RCTs. During the initial review of the literature and data abstraction phase, we observed that the evidence concerning the organization of health care delivery (KQ 3a) was limited, and though we attempted to address this key question, we did not find evidence to support the impact of CDSSs/KMSs. The key categories of outcomes related to KQs 3b and 3c are:

1. **Process outcomes** (the recommended preventive care, clinical study, or treatment was ordered, completed, and adhered to)
2. **Economic outcomes** (cost and cost-effectiveness)
3. **Use and implementation outcomes** (acceptance, satisfaction, use, implementation)
4. **Clinical outcomes** (length of stay, morbidity, mortality, measure of health-related quality of life, adverse events)
5. **Relationship-centered outcomes** (patient satisfaction)
6. **User workload and efficiency outcomes** (number of patients seen, clinician workload, efficiency)

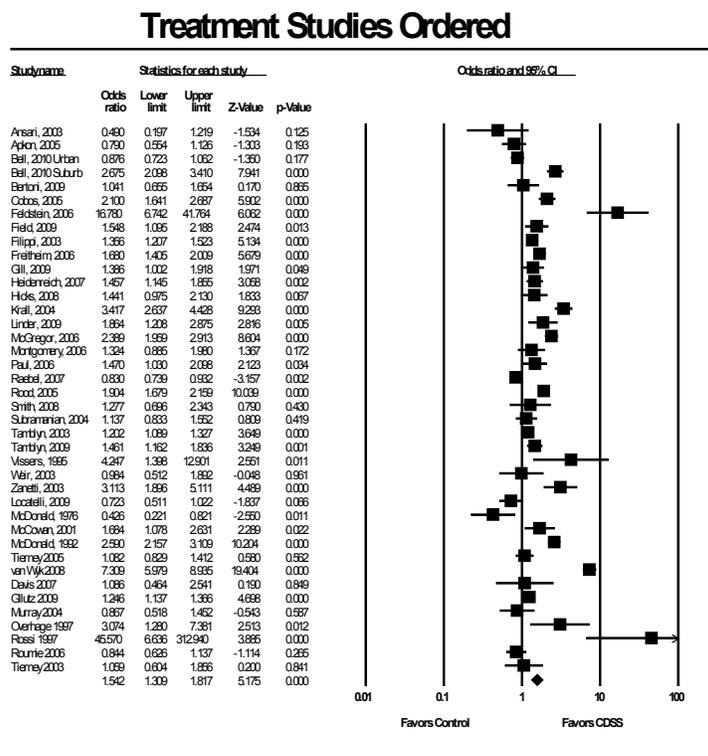
Impact on Process Outcomes

Recommendations to order/prescribe treatment. We identified 61 of the 131 eligible studies (46.6%) that specifically examined the impact of CDSSs/KMSs on the ordering and prescribing of therapy. These studies are summarized in Table H-1 of Appendix H. Of these 61 studies, 37 (61.7%) were conducted in the U.S.,^{24,27,33-35,38,40,43,57,58,64,68,73,79,81-83,86-92,94,100,106,107,112-121} 18 (29.5%) in Europe,^{29,31,32,39,47,56,61,62,66,67,75,84,85,122-129} 4 (6.6%) in Canada,^{28,53,54,108} 1 (1.6%) in multiple countries,⁴⁴ and 1 (1.6%) location was not reported.⁹³ Twenty-two of the studies (36.1%) were implemented in an academic setting,^{28,38,40,43,44,47,53,57,66,67,73,79,86-88,94,112,114-118,121,125} 20 (32.8%) in a community setting,^{27,29,31,32,35,39,56,58,61,62,68,75,85,91,106,119,120,122,124,128,129} 12 (19.7%) in both academic and community settings,^{24,33,64,82-84,90,93,100,107,123,126,127} 4 (6.6%) in a VA setting,^{34,81,89,92} 1 (1.6%) in both academic and VA settings,¹¹³ and 2 (3.3%) did not have the

setting clearly reported.^{54,108} Eleven studies (18%) evaluated the systems in the inpatient environment,^{43,44,47,57,87,114,115,117,118,120,128} 46 (75.4%) in the ambulatory environment,^{24,27,29,31-33,35,38-40,53,54,56,58,61,62,64,68,73,75,79,81-86,88-92,94,100,106-108,112,113,116,119,121-127,129} 2 (3.3%) in both inpatient and outpatient environments,^{34,93} 1 (1.6%) in the emergency department,^{66,67} and 1 (1.6%) in a long-term care facility.²⁸ Duration of the evaluation period across the studies ranged from 10 weeks⁴⁷ to 4.2 years.⁸² Forty-four interventions (72.1%) were implemented using a system developed within the health care organization,^{24,27,34,38-40,44,47,53,54,57,61,62,64,68,73,79,81-83,86,87,89-92,94,106-108,112-121,123,124,126-129} 12 (19.7%) were implemented using a commercially available system,^{28,31-33,35,43,56,58,75,85,100,122,125} and 5 sources (8.2%) were not clearly described.^{29,66,67,84,88,93} Seven systems (11.5%) aided health care providers with tasks for diagnosis,^{44,56,58,64,66,67,85,106} 39 (43.8%) for pharmacotherapy,^{28,29,31-35,38,43,44,53,54,57,62,64,81,82,85,87-91,93,94,100,106-108,112,115,116,118-121,124-129} 5 (8.2%) for laboratory test ordering,^{33,38,87,94,107} 24 (39.3%) for chronic disease management,^{24,27,33,39,47,58,61,62,64,68,73,79,81,83,84,86,90-92,94,116,121-124} and 10 (16.4%) for additional clinical tasks.^{40,56,58,66,67,75,94,107,113,114,117} Fifty-two of the systems (85.2%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{24,27-29,31-35,39,43,44,47,53,54,56-58,61,64,68,73,75,79,81-84,86-89,91,92,94,100,106-108,112-119,121,122,124-129} 4 (6.6%) delivered recommendations outside of the HCP-patient encounter,^{38,40,93,120} 2 (3.3%) provided recommendations using both mechanisms,^{66,67,123} and 3 (4.9%) did not clearly describe how the CDSS was delivered.^{62,85,90} Nine (14.8%) of the interventions required a mandatory response,^{35,57,66,67,88,91,100,114,118,119} 4 (6.6%) required the HCP to justify the reason for not complying with the recommendation,^{61,89,108,117} 7 (11.5%) required a noncommittal acknowledgement,^{28,33,73,86,87,94,115} and 41 (67.2%) did not have a response requirement.^{24,27,29,31,32,34,38-40,43,44,47,53,54,56,58,62,64,68,75,79,81-85,90,92,93,106,107,112,113,116,120-129} In 32 studies (52.4%), the recommendations were integrated within a CPOE or EHR,^{24,27-29,31-33,35,43,47,53,54,56-58,64,79,81-83,85-88,90,100,108,112,115,117-119,126,127} 1 (1.6%) provided recommendations via an online system, 10 (16.4%) delivered recommendations via fax or computer printout,^{34,38,40,62,89,92-94,116,120,121} 11 (18%) via a standalone system,^{39,44,61,66-68,84,106,124,125,128,129} 5 (8.2%) had a combination of two of these formats,^{73,91,107,114,123} and 3 (4.9%) did not clearly describe the format.^{75,113,122} The recommendations were automatically delivered to the HCP in 49 studies (80.3%).^{24,27-29,31-35,38,40,43,44,47,53,54,56-58,61,62,73,79,81-83,86-94,100,107,108,112-121,126-129} In 8 studies (13.1%), the HCP had to initiate an action to receive the recommendation,^{39,66-68,85,106,123-125} 1 study (1.6%) delivered recommendations using both modes,⁶⁴ and mode was not reported in 3 studies (4.9%).^{75,84,122} Thirty-six studies (59%) received a “Good” quality score,^{24,27,28,34,35,38,40,43,44,47,53,54,56-58,64,66-68,73,81,83,86-91,93,94,100,114,117,118,120,123,124} 17 (28.3%) had a “Fair” score,^{29,31,32,39,61,82,84,85,92,106,108,112,116,119,121,125-129} and 8 (13.1%) received a “Poor” score.^{33,62,75,79,107,113,115,122}

We conducted a meta-analysis (Figure 3) that focused on CDSS studies in which at least one outcome was related to ordering treatments or prescribing therapies. Of the 61 studies (46.6%) that assessed a response to recommendations for ordering treatment or prescribing therapies, 39 studies (63.9%) included data with a common dichotomous endpoint and were included in the meta-analysis.^{24,27-29,31-35,38-40,43,44,47,53,54,56-58,61,62,64,66-68,73,79,81-93} The overall effect of clinical decision support on treatment or prescribing outcomes was statistically significant and estimated as an odds ratio of 1.55 (95% CI 1.28 to 1.89). Thus, intervention providers with decision support were almost 1.6 times more likely to order the appropriate treatment or prescribe the correct therapy than control providers.

Figure 3. Meta-analysis of Recommended Treatment Studies Ordered



Five high-quality, recently published papers^{24,28,68,83,100} in which the CDSS interventions were thoroughly described were examined in detail to guide observations about the larger group of studies that evaluated treatment and prescribing outcomes. Bell et al. (2010)²⁴ assessed treatment reminders to improve provider adherence to national asthma guidelines at 12 academic and community clinics for 2.4 years and found that the number of prescriptions for controller medication significantly increased in the intervention urban practices ($P = 0.006$). Bertoni et al. (2009)⁶⁸ evaluated a handheld CDSS that calculated the Framingham risk score for cardiac disease and delivered recommendations for lipid screening and management-based national guidelines at 66 community clinics. They reported that the appropriate treatment of cholesterol levels decreased in both the intervention and control practices but that the net change favored the intervention practices (+9.7%, CI 2.8% to 16.6%, $P < 0.01$); that overtreatment of dyslipidemia with inappropriate prescriptions decreased in the intervention practices (net change, -4.9%, $P = 0.01$); and that after 4 months into the study, provision of appropriate prescriptions decreased in both groups ($P = 0.37$). Field et al. (2009)²⁸ evaluated medication dose adjustment recommendations for long-term care residents with renal insufficiency in 22 long-term care units for 12 months and reported that overall final medication orders were more often appropriate in the intervention units (RR 1.2 [1.0, 1.4]). Fortuna et al. (2009)¹⁰⁰ evaluated prescribing alerts for hypnotic medications embedded in an EHR among 257 providers over 12 months and found that the relative risk of prescribing a medication was less in both the alert group (RR 0.74; 95% CI 0.57–0.96) and the alert-plus-provider-education group (RR 0.74; 95% CI 0.58 to 0.97). Hicks et

al. (2008)⁸³ investigated diabetes and coronary artery disease treatment reminders to improve provider adherence to national guidelines in 14 clinics for 18 months and found a significant improvement in the rates at which appropriate medications were prescribed ($P < 0.001$).

From the research studies cited above, we conclude that there is strong evidence from academic and community ambulatory settings that system-integrated, locally developed CDSSs that provided recommendations to providers synchronously at the point of care and did not require a mandatory clinician response are effective at improving appropriate ordering of treatment.^{24,27-29,31-35,38,40,44,54,56,57,61,62,64,68,83,87-89,94,113-115,117,118,120,122,124,125,128} Twenty studies

(32.8%) that support this conclusion evaluated more than 2000 patients.^{24,29,31-33,35,38,43,44,53,54,61,62,64,68,75,83,87,108,115,123}

Notably with regard to improving the quality of care, only a few of the studies that demonstrated effectiveness of CDSSs assessed the effect of appropriate ordering of treatment on clinical outcomes^{31,32,34,40,44,57,62,87,113,114} or on economic outcomes.^{31,32,44,61,87,122}

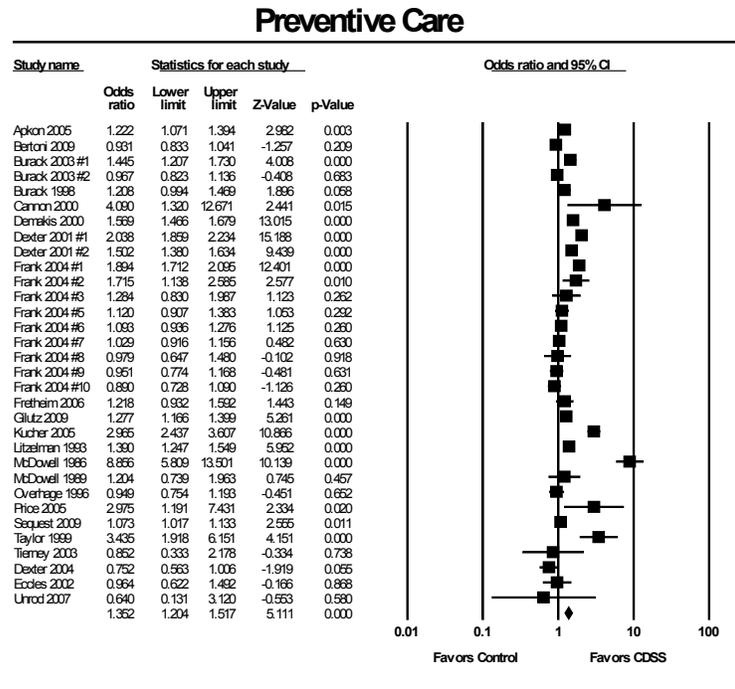
In addition to the 20 studies that reported statistical significance, there is supportive evidence from the academic and community ambulatory settings that locally developed CDSSs that provided recommendations to providers synchronously at the point of care and did not require a mandatory clinician response demonstrated a trend toward improving appropriate ordering of treatment.^{39,43,47,53,66,67,75,79,82,92,93,106,108,112,123,129} With regard to improving the quality of care, only a few of the studies that demonstrated a trend toward effectiveness of CDSSs assessed the effect of appropriate ordering of treatment on clinical outcomes^{39,43,79,92} or on economic outcomes.^{43,79}

Recommendations to order/complete a preventive care service. We identified 40 of the 131 eligible studies (30.5%) that specifically examined the impact of CDSSs/KMSs on ordering or completing recommended preventive care services. These studies are summarized in Table H-2 of Appendix H. Of these 40 studies, 26 (65%) were conducted in the U.S.,^{25,26,33,36,37,51,55,58-60,68-70,72,74,79,94,107,130-139} 5 (12.5%) in Europe,^{4,31,32,56,62,104} 6 (15%) in Canada,^{41,65,71,140-142} 2 (5%) in Australia,^{30,143} and 1 (2.5%) in New Zealand.¹⁴⁴ Eighteen of the studies (45%) were implemented in an academic setting,^{26,36,37,41,60,70-72,79,94,133-137,139,141-143} 15 (37.5%) in a community setting,^{4,30-32,51,56,58,59,62,68,69,74,130,131,138,140,144} 4 (10%) in both academic and community settings,^{33,55,107,132} 1 (2.5%) in a VA setting,²⁵ and 2 (5%) did not specify the location.^{65,104} Four studies (10%) evaluated the systems in the inpatient environment^{26,36,70,72} and 36 (90%) in the ambulatory environment.^{4,25,30-33,37,41,51,55,56,58-60,62,65,68,69,71,74,79,94,104,107,130-144} Duration of the evaluation period across the studies ranged from 6 weeks¹⁴³ to 40 months.³⁶ Twenty-four interventions (57.5%) were implemented using a system developed within the specific health care organization,^{25,26,36,37,59,60,62,68-72,74,79,94,104,107,130,131,133-136,139,141,142} 10 (25%) were implemented using a commercially available system,^{4,31-33,51,56,58,65,132,143,144} and 6 had a source that was not clearly described.^{30,41,55,137,138,140} Four systems (10%) aided health care providers with tasks for diagnosis,^{56,58,60,104} 7 (17.5%) for pharmacotherapy,^{26,31-33,62,94,107,143} 11 (27.5%) for chronic disease management,^{4,25,33,58,62,68,79,94,135,138,140} 10 (25%) for laboratory test ordering,^{33,37,51,55,94,104,107,135,137,139} 3 (7.5%) for initiating discussions with patients,^{55,74,140} and 32 (80%) for additional clinical tasks.^{25,26,30-33,36,37,41,51,55,56,58,59,62,65,69-72,94,104,107,130-137,139,141,142,144} Thirty-eight (95%) of the systems delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{4,25,26,31-33,36,37,41,51,55,56,58-60,65,68-72,74,79,94,104,107,130-144} and for two studies (5%), the delivery mechanism for the CDSS was not clearly described.^{30,62} Four (10%) of the interventions required a mandatory response,^{26,36,51,60} 3 (7.5%) required the HCP to justify the reason for not complying with the

recommendation,^{130,131,134,136,137} 11 (27.5%) did not have a response
 requirement,^{31,32,58,59,68,69,71,107,135,141,142,144} 5 (12.5%) required a noncommittal
 acknowledgement,^{33,72,94,133,139} 1 (2.5%) required both a mandatory response and justification for
 not complying with the recommendation;³⁷ and in 16 studies (40%), it was assumed that there
 was no user response requirement or it was unclear to the abstractor if such requirement was
 present.^{4,25,30,41,55,56,62,65,70,74,79,104,132,138,140,143} In 13 studies (33.3%), the recommendations were
 integrated within a CPOE or EHR,^{4,26,30-33,36,51,56,58,70,79,132,144} 18 (45%) delivered via fax or
 computer printout,^{37,41,55,59,62,69,71,72,74,94,130,131,134-139,141,142} 5 (12.5%) via a standalone
 system,^{60,65,68,104,143} 2 (5%) via online recommendations,^{133,140} and 2 (5%) were integrated both
 within a CPOE or EHR and delivered via fax or computer printout.^{25,107} The recommendations
 were automatically delivered to the HCP in 33 studies (82.5%),<sup>4,25,26,31-33,36,37,41,51,55,56,58-60,62,69-
 72,74,79,94,107,130-132,134-139,141-143</sup> in 5 studies (12.5%), the HCP had to initiate an action to receive the
 recommendation,^{65,68,104,133,144} and in 2 studies (5%) the mode for assessing the CDSS was not
 clearly described.^{30,140} Eighteen studies (45%) received a “Good” quality score,<sup>25,26,36,55,56,58,59,68-
 70,72,94,130,131,135,138,139,143,144</sup> 15 (38.5%) had a “Fair” score,^{4,30-32,37,41,51,60,71,74,132,134,136,137,140-142} and
 7 (17.9%) received a “Poor” score.^{33,62,65,79,104,107,133}

We conducted a meta-analysis (Figure 4) that focused on CDSS studies in which at least one
 outcome was related to ordering or completing preventive care services. Of the 40 studies that
 assessed a response to recommendations for ordering treatment or prescribing therapies, 22
 studies (55%) included data with a common dichotomous endpoint and were included in the
 meta-analysis.^{4,25,26,30-32,36,37,41,51,55,58-60,62,65,68-72,74,79,139} Clinical decision support systems were
 found to have a statistically significant impact on the ordering or completing of preventive care
 services, with the overall effect of clinical decision support having an odds ratio of 1.37 (95% CI
 1.16 to 1.62).

Figure 4. Meta-analysis of Recommended Preventive Care Service Ordered



One high-quality, recently published paper⁶⁸ in which the CDSS intervention was thoroughly described was examined in detail to guide observations about this group of studies. Bertoni et al. (2009)⁶⁸ assessed a PDA-based decision support system that calculated the Framingham risk score and provided recommendations for lipid screening and management-based national guidelines and related to the appropriate ordering and completion of preventive care services. They found that the lipid level screening rate increased in both the intervention and control practices (43.6% to 49% [intervention]; 40.1% to 50.8% [control]; net difference -5.3% P = 0.22).

From the research studies cited above, we conclude that there is strong evidence from academic and community ambulatory settings that locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care and did not require a mandatory clinician response are effective at improving appropriate ordering of preventive care procedures.^{25,26,33,36,37,55,56,58-60,62,70,133-138,140} This conclusion is supported by evidence from 10 studies that included evaluation periods longer than 1 year^{25,26,33,36,55,59,62,70,137,138} and 10 studies that were evaluated with more than 2000 patients.^{25,26,33,36,37,55,59,62,70,137,138} However, only five studies were published after 2008.^{33,56,62,138,140} With regard to improving the quality of care, very few of the studies demonstrated effectiveness of CDSSs designed to promote the appropriate ordering of preventive care procedures on clinical outcomes^{36,62} or on economic outcomes.⁵⁸ In addition to the 8 studies that achieved statistical significance, there is supportive evidence from the academic and community ambulatory settings that locally developed CDSSs that automatically delivered

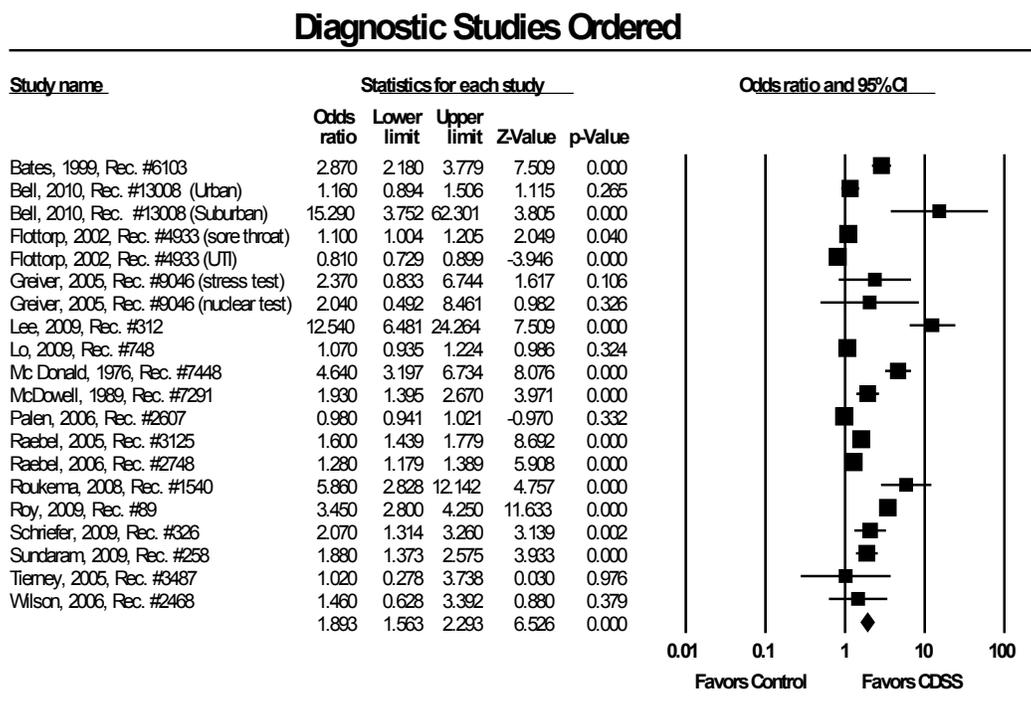
system-initiated (push) recommendations to providers synchronously at the point of care are and did not require a mandatory clinician response demonstrated a trend toward improving appropriate ordering of preventive care procedures.^{30-32,51,65,69,71,74,104,130-132,139,141-144} This observation showing a trend for effectiveness is supported by evidence from 7 studies that included evaluation periods longer than 1 year^{31,32,51,69,71,130,131,141,142} and 11 studies that were evaluated with more than 2000 patients.^{30-32,51,68,69,130-132,139,141-143} However, only two of these studies were published after 2008.^{51,68,132} Notably, with regard to improving the quality of care, very few of the studies that demonstrated a trend toward effectiveness of CDSSs assessed the effect of appropriate ordering of preventive care procedures on clinical outcomes^{31,32,51} or on economic outcomes.^{31,32,71,104} With regard to the future direction of the field of using mobile devices to enhance the delivery and quality of care, two studies demonstrated that use of a handheld computer-based decision support program at the point of care led to higher rates of lipid screening⁶⁸ and of preventive care screening for cervical and colorectal cancer, hyperlipidemia, hypertension, and in promoting prophylaxis with acetylsalicylic acid.⁶⁵

Recommendations to order/complete a clinical study. We identified 24 of the 131 eligible studies (18.3%) that specifically examined the impact of CDSSs/KMSs on the ordering and completion of recommended clinical studies. Examples of these interventions included reminders to order blood tests when ordering a medication, alerts to update a laboratory test, recommendations to refer patients for genetic testing, notices for x-ray orders, and suggestions to diagnose dementia and obesity. These studies are summarized in Table H-3 of Appendix H. Of these 24 studies, 13 (54.2%) were conducted in the U.S.,^{23,24,38,45,46,50,52,63,77-79,145,146} 7 (29.2%) in Europe,^{48,49,75,80,99,109,147} 3 (12.5%) in Canada,^{42,76,148} and 1 (4.2%) in an unspecified country.¹⁴⁹ Nine of the studies (37.5%) were implemented in an academic setting,^{23,38,42,45,46,50,63,79,145} 6 (25%) in a community setting,^{49,75,80,99,109,147} 5 in both academic and community settings,^{24,76,77,146,148} 1 (4.2%) in a VA setting,⁵² and 3 (12.5%) in settings not clearly described.^{48,78,149} Two studies (8.3%) evaluated the systems in the inpatient environment,^{23,145} 19 (79.2%) in the ambulatory environment,^{24,38,42,45,46,50,52,63,75-80,99,109,146,147,149} and 3 (12.5%) in the emergency department.^{48,49,148} Duration of the evaluation period across the studies ranged from 14 weeks¹⁴⁹ to 2.4 years.²⁴ Eighteen interventions (75%) were implemented using a system developed within the specific health care organization,^{23,24,38,42,45,48,49,52,63,76,77,79,80,109,145,146,148,149} 4 (16.7%) were implemented using a commercially available system,^{75,78,99,147} and 2 (8.3%) were implemented in a site that was not clearly described.^{46,50} Eight systems (33.3%) aided health care providers with tasks for diagnosis,^{42,48-50,63,76,145,147} 1 (4.2%) for pharmacotherapy,³⁸ 4 (16.7%) for chronic disease management,^{24,50,79,147} 13 (54.2%) for laboratory test ordering,^{23,38,45,46,48,52,76-78,109,146,148,149} 1 (4.2%) for initiating discussions with patients,⁸⁰ and 4 (16.7%) for additional clinical tasks.^{75,80,99,145} Twenty-four of the systems (100%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{23,24,42,45,46,48-50,52,63,75-80,99,109,145-149} and one (4.2%) delivered recommendations outside of the HCP-patient encounter.³⁸ Four of the interventions (16.7%) required a mandatory response,^{45,46,145,148} 2 (8.3%) required the HCP to justify the reason for not complying with the recommendation,^{23,52} 5 (20.8%) did not have a response requirement,^{42,77,109,146,149} 1 (4.2%) required a noncommittal acknowledgement,⁷⁸ and in 12 studies (50%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{24,38,48-50,63,75,76,79,80,99,147} In 16 studies (66.7%), the recommendations were integrated within a CPOE or EHR,^{23,24,45,46,48,50,52,77-79,109,145-149} 2 (8.3%) were delivered via fax or computer printout,^{38,42} 3 (12.5%) via a standalone system,^{49,63,76}

and 3 (12.5%) via other delivery methods.^{75,80,99} The recommendations were automatically delivered to the HCP in 16 studies (66.7%);^{23,24,38,42,45,46,48,50,52,77-79,146-149} in 5 studies (20.8%), the HCP had to initiate an action to receive the recommendation,^{49,76,80,109,145} and in 3 studies (12.5%) the mode of CDSS delivery was not clearly described.^{63,75,99} Fourteen studies (58.3%) received a “Good” quality score,^{24,38,45,46,48,50,52,77,78,109,146-149} 6 (25%) had a “Fair” score,^{23,42,49,63,99,145} and 4 (16.7%) received a “Poor” score.^{75,76,79,80}

We conducted a meta-analysis (Figure 5) Figure 1 that focused on CDSS studies in which at least one outcome was related to ordering or completing of recommended clinical studies. Of the 24 studies that assessed a response to recommendations for ordering or completing clinical studies, 17 (70.8%) included data with a common dichotomous endpoint and were included in the meta-analysis.^{23,24,38,42,45,46,48-50,52,63,75-80} Clinical decision support systems were found to have a statistically significant impact on the ordering or completing of clinical studies with the overall effect of clinical decision support having an odds ratio of 2.04 (95% CI 1.49 to 2.81).

Figure 5. Meta-analysis of Recommended Clinical (Diagnostic) Studies Ordered



Three high-quality, recently published papers^{24,52,77} in which the CDSS interventions were thoroughly described were examined in detail to guide observations about this group of studies. Bell et al. (2010)²⁴ evaluated treatment reminders to improve provider adherence to asthma guidelines in part through the appropriate ordering and completion of clinical studies. They found that rates of performing spirometry significantly improved in the suburban intervention practices (P = 0.003). Lo et al. (2009)⁷⁷ assessed reminders to order appropriate laboratory tests in 22 clinics for 6 months and reported that there was no difference between intervention and

control provider with regard to appropriately ordering laboratory tests within 14 days of a medication prescription (41% versus 39%) (OR 1.048, CI 0.753 to 1.457, P = 0.782). Sundaram et al. (2009)⁵² evaluated reminders to assess HIV risk behaviors or to offer HIV testing on 32 providers for 9 months and reported no change in testing rates between the intervention and control providers (0.29% versus 0.52%) (P = 0.75).

From the research reported in this section, we conclude that there is modest evidence that CDSSs can improve the appropriate ordering of clinical studies. Although there was strong evidence from 14 studies (58.3%) conducted in the academic and community ambulatory settings that CDSSs integrated in CPOE or EHR systems and locally developed CDSSs that provided recommendations to providers synchronously at the point of care and did not require a mandatory clinician response are effective at improving appropriate ordering of clinical studies,^{23,24,38,45,46,48-50,63,99,109,147-149} 2 of the 3 key papers reported a negative impact of CDSSs on the ordering of clinical studies. Therefore, our confidence in the impact is lessened. Of those studies that did report a positive effect, 9 (37.5%) were evaluated with more than 2000 patients.^{23,24,42,45,46,75,77,147,148} With regard to improving the quality of care, very few of the studies that demonstrated effectiveness of CDSSs assessed the effect of appropriate ordering of clinical studies on clinical outcomes⁴⁸ or on economic outcomes.²³ In particular, while the Roukema et al.⁴⁸ study evaluated a decision support intervention that successfully promoted appropriate ordering of laboratory tests, it was also associated with an increase in the length of stay in the emergency department. There is limited supporting evidence from the academic and community ambulatory settings that locally developed CDSSs that provided recommendations to providers synchronously at the point of care and did not require a mandatory clinician response demonstrated a trend toward improving appropriate ordering of clinical studies.^{42,75-77,80,146} Notably with regard to improving the quality of care, none of the studies that demonstrated a trend toward effectiveness of CDSSs assessed the effect of appropriate ordering of clinical studies on clinical outcomes, and very few assessed the effect on economic outcomes.^{42,80}

Impact on user knowledge. We identified 5 of the 131 eligible studies (3.8%) that specifically examined the impact of CDSSs/KMSs on user knowledge. These studies are summarized in Table H-4 of Appendix H. Of these 5 studies, one (20%) was conducted in the U.S.,⁹⁸ two (40%) in Europe,^{99,104} one (20%) in Canada,¹⁴⁰ and one (20%) in multiple countries.²² Three of the studies (60%) were implemented in a community setting^{98,99,140} and two (40%) in an unreported setting.^{22,104} Four of the studies (80%) evaluated the systems in the in the ambulatory environment^{98,99,104,140} and one (20%) did not clearly report the setting.²² Duration of the evaluation period across the studies ranged from 3 months²² to 1 year.⁹⁹ Two interventions (40%) were implemented using a system developed within the specific health care organization,^{98,104} two (40%) were implemented using a commercially available system,^{22,99} and one (20%) did not specify a source of the CDSS/KMS.¹⁴⁰ One system (20%) aided health care providers with tasks for diagnosis,¹⁰⁴ one (20%) for chronic disease management,¹⁴⁰ one (20%) for laboratory test ordering,^{104,107} one (20%) for initiating discussions with patients,¹⁴⁰ and three (60%) for additional clinical tasks.^{22,98,99,98,99,104,107} Four (80%) of the systems delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter^{98,99,104,140} and one (20%) did not report a relation.²² One (20%) of the interventions required a mandatory response,²² one of the interventions (20%) did not have a response requirement,⁹⁸ and in three studies (60%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{99,104,140} In one study (20%), the recommendations were integrated

within a CPOE or EHR;⁹⁸ 1 (20%) via a standalone system,¹⁰⁴ 2 (40%) delivered online,^{22,140} and the format of one study (20%)⁹⁹ was not clear. In three studies (60%) the HCP had to initiate an action to receive the recommendation^{22,98,104} and two studies (40%) did not clearly describe how recommendations were delivered.^{99,140} No studies received a “Good” quality score, four (80%) had a “Fair” score,^{22,98,99,140} and one (20%) received a “Poor” score.^{104,107}

None of the 10 key papers reported data describing the impact of CDSSs on user knowledge. Of the studies that reported user knowledge data, Alper et al. (2005)²² reported that an electronic knowledge resource accessed by providers during and outside of the HCP-patient encounter increased the number of questions answered (75.8% versus 71.2%) and the number of questions for which the answer changed decisionmaking (64.6% versus 23.4%); however, the number of questions for which the providers did not find an answer that could have changed decisionmaking did not improve with access to the resource (19.6% versus 23.4%). Del Fiore et al. (2008)⁹⁸ found providers reported that in 62% of sessions, the use of an information retrieval tool embedded in an EHR system that provided access to topic or nonspecific links to clinical resources to aid in answering clinicians’ questions at the point of care enhanced their decisions or knowledge. Holbrook et al. (2009)¹⁴⁰ found that 48% of providers who used a Web-based diabetes tracker that included diabetes care reminders reported that their knowledge of diabetes blood sugar control targets had improved. Emery et al. (2007)⁹⁹ reported that a cancer risk assessment tool improved clinician confidence in managing the risk of familial cancer. Hobbs et al. (1996)¹⁰⁴ found that providers reported their knowledge of lipid disorders improved; however, no distinction was made between those who received the intervention (a standalone decision support system for the management of hyperlipidemia) and those who did not.

From the research included in this section, we conclude that there is limited evidence regarding the effect of CDSSs/KMSs on user knowledge.

Impact on Economic Outcomes

Cost. We identified 20 of the 131 eligible studies (15.3%) that specifically examined the impact of CDSSs/KMSs on cost. These studies are summarized in Table H-5 of Appendix H. Of these 20 studies, 11 (55%) were conducted in the U.S.,^{23,43,58,73,79,86,87,91,145,150,151} 6 (30%) in Europe,^{31,32,61,80,104,110,111,122} 1 (5%) in Canada,⁴¹ 1 (5%) in multiple countries,⁴⁴ and 1 (5%) did not report a location.¹⁵² Ten (50%) of the studies were implemented in an academic setting,^{23,41,43,44,73,79,86,87,145,150} 9 (45%) in a community setting,^{31,32,58,61,80,91,110,111,122,151,152} and 1 (5%) did not report a setting.¹⁰⁴ Five studies (25%) evaluated the systems in the inpatient environment^{23,43,44,87,145} and 15 (75%) in the ambulatory environment.^{31,32,41,58,61,73,79,80,86,91,104,110,111,122,150-152} Duration of the evaluation period across the studies ranged from 25 days¹⁵² to 2.5 years.⁹¹ Fourteen interventions (70%) were implemented using a system developed within the specific health care organization,^{23,44,61,73,79,80,86,87,91,104,145,150-152} 5 (25%) were implemented using a commercially available system,^{31,32,43,58,110,111,122} and 1 (5%) had a system that was not clearly described.⁴¹ Four systems aided health care providers with tasks for diagnosis,^{44,58,104,145} five (25%) for pharmacotherapy,^{31,32,43,44,87,91} eight (40%) for chronic disease management,^{58,61,73,79,86,91,110,111,122} four (20%) for laboratory test ordering,^{23,87,104,152} two (10%) for initiating discussions with patients,^{80,151} and eight (40%) for additional clinical tasks.^{31,32,41,58,80,104,145,150,151} Nineteen of the systems (95%) delivered recommendations in real time to enable decisionmaking during the HCP-patient

encounter,^{23,31,32,41,43,44,58,61,73,79,80,86,87,91,104,110,111,122,145,150,152} and 1 (5%) delivered recommendations outside of the HCP-patient encounter.¹⁵¹ Three of the interventions (15%) required a mandatory response,^{91,110,111,145} two (10%) required the HCP to justify the reason for not complying with the recommendation,^{23,61} five (75%) did not have a response requirement,^{31,32,44,58,150,152} three (15%) required a noncommittal acknowledgement,^{73,86,87} and in seven studies (35%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{41,43,79,80,104,122,151} In 9 studies (45%), the recommendations were integrated within a CPOE or EHR,^{23,31,32,43,58,79,86,87,145,152} three (15%) were delivered via fax or computer printout,^{41,150,151} one (5%) was integrated within a CPOE or EHR and via delivered via fax or computer printout,⁷³ four (20%) via a standalone system,^{44,61,104,110,111} and three (15%) had other formats.^{73,91,122} The recommendations were automatically delivered to the HCP in 15 studies (75%);^{23,31,32,41,43,44,58,61,73,79,86,87,91,150-152} in 4 studies (20%), the HCP had to initiate an action to receive the recommendation,^{80,104,110,111,145} and 1 (5%) study did not have a mode clearly reported.¹²² Nine studies (45%) received a “Good” quality score,^{43,44,58,73,86,87,91,110,111,152} six (30%) had a “Fair” score,^{23,31,32,41,61,145,151} and five (25%) received a “Poor” score.^{79,80,104,122,150}

One high-quality, recently published paper^{110,111} in which the CDSS intervention was thoroughly described was examined in detail to guide observations about this group of studies. Cleveringa et al. (2008)^{110,111} evaluated a standalone system that focused on decreasing cardiovascular risk in 3391 patients with type 2 diabetes over 12 months by including an algorithm based on the Dutch type 2 diabetes diagnostic and treatment guidelines. They found that use of the CDSS to provide patient-specific treatment recommendations reduced cardiovascular risk, but it was more costly as patients in the intervention group incurred higher total costs than those in the control group (€1,415, P = NS). However, though there was an enormous variability in the studies reporting cost data, other studies found a cost savings between \$6,000 (through recommendations for the appropriate use of abdominal radiograph orders) and \$84,194 (through reminders about the appropriate use of antimicrobials). Of those reporting costs savings, Cobos et al. (2005)⁶¹ reported a significant cost savings by reducing the number of lipid-lowering drug prescriptions during the 1-year evaluation period between 20.8 and 24.9% from a CDSS that provided hypercholesterolemia treatment and followup visit recommendations.⁶¹ A second study published in 2008⁹¹ reported that a telemedicine intervention for the medication management of cardiovascular risk found that the intervention resulted in cost savings for outpatient costs (-\$288) (95% CI -\$25 to -\$550) and total costs (-\$2,311) (95% CI -\$266 to -\$4667).

From the research included in this section, we conclude that there is modest evidence from the inpatient and ambulatory settings that locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrated a trend toward lower treatment costs, total costs, and greater cost savings than the control groups and other non-CDSS intervention groups (e.g., patient education intervention, pharmacist intervention).^{23,31,32,43,44,61,73,86,87,91,145,150,151} This conclusion is supported by evidence from six studies that included evaluation periods longer than 1 year^{31,32,61,73,86,91,151} and six studies with more than 2000 patients.^{23,31,32,43,44,61,87} Notably, all except one study was published prior to 2008.⁹¹

Cost-effectiveness. We identified 6 of the 131 eligible studies (4.6%) that specifically examined the impact of CDSSs/KMSs on cost-effectiveness. These studies are summarized in Table H-6 of

Appendix H. Of these six studies, two (33.3%) were conducted in Europe^{31,32,110,111} and four (66.7%) in Canada.^{41,42,71,141} Four of the studies (66.7%) were implemented in an academic setting^{41,42,71,141} and two (33.3%) in a community setting.^{31,32,110,111} All six studies (100%) evaluated the systems in the ambulatory environment.^{31,32,41,42,71,110,111,141} Duration of the evaluation period across the studies ranged from 10 weeks⁴¹ to 15 months.⁴² Three interventions (50%) were implemented using a system developed within the specific health care organization,^{42,71,141} two (33.3%) were implemented using a commercially available system,^{31,32,110,111} and one (16.7%) did not clearly describe a source.⁴¹ One system (16.7%) aided health care providers with tasks for diagnosis,⁴² one (16.7%) for pharmacotherapy,^{31,32} one (16.7%) for chronic disease management,^{110,111} and four (66.7%) for additional clinical tasks.^{31,32,41,71,141} All six of the systems (100%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter.^{31,32,41,42,71,110,111,141} One of the interventions (16.7%) required a mandatory response,^{110,111} four (66.7%) did not have a response requirement,^{31,32,42,71,141} and in one study (16.7%) it was unclear to the abstractor if such requirement was present.⁴¹ In one (16.7%) study, the recommendations were integrated within a CPOE or EHR,^{31,32} four (66.7%) were delivered via fax or computer printout^{41,42,71,141} and one (16.7%) via a standalone system.^{110,111} The recommendations were automatically delivered to the HCP in five (83.3%) studies,^{31,32,41,42,71,141} and the HCP had to initiate an action to receive the recommendation in one study (16.7%).^{110,111} One (16.7%) study received a “Good” quality score,^{110,111} and five (83.3%) had a “Fair” score.^{31,32,41,42,71,141}

One high-quality, recently published paper^{110,111} was examined in detail to guide observations about this group of studies. As described in the previous section, Cleveringa et al. (2008)^{110,111} evaluated a standalone system that provided clinicians with treatment recommendations for decreasing cardiovascular risk factors for type 2 diabetic patients and related to the resulting benefits cost-effectiveness. They found that the intervention group incurred higher total costs (€1,415) and exceeded the study’s established willingness to pay QALY threshold of €20,000. The remaining studies found that the intervention group tended to be more cost-effective than usual care or other interventions (e.g., patient letters, telephone reminders). Rosser 7131 et al. (1992)¹⁴¹ assessed the cost-effectiveness of three interventions for improving provider compliance with reminders for tetanus vaccination. The effectiveness of each intervention was assessed based on provider time, time to prepare and deliver recommendations, and supply costs of mailing patient reminder letters. Among the three groups, they found that the cost per additional vaccination was \$0.43 or \$0.22 depending on the salary level for the physician reminders; \$5.43 or \$4.43 depending on the nurse salary level for the telephone reminders; and \$6.05 for the patient letter reminders. McDowell et al. (1989)⁴² evaluated the cost-effectiveness of three interventions for improving blood pressure screening and assessed the effectiveness based on staff and material costs of delivering the recommendations. They reported that the cost per blood pressure reading was \$1.70 or \$1.33 depending on the salary level for physician reminders; \$31.27 or \$22.47 depending on the nurse salary level for telephone reminders; and \$14.37 for the patient letter reminders. Fretheim et al. (2006)^{31,32} evaluated the cost-effectiveness of prescribing recommendations for antihypertensive and cholesterol-lowering drugs and estimated that the cost of using the CDSS was \$183 per additional patient being started on a thiazide.

From the research included in this section, we conclude that there is conflicting evidence from the ambulatory setting regarding the cost-effectiveness of CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of

care. Some studies demonstrated a trend toward cost-effectiveness,^{31,32,42,141} while Cleveringa et al. (2008, 2010)^{110,111} did not find that CDSS was cost-effective. There was favorable evidence from studies with evaluation periods of at least 1 year and that evaluated at least 2000 patients that the CDSS was more cost-effective than usual care.^{31,32,42,141} Notably, none of these studies was published after 2008; one was published in 1989⁴² and the other in 1992.¹⁴¹

Impact on Use and Implementation Outcomes

HCP satisfaction. We identified 18 of the 131 eligible studies (13.7%) that specifically examined the impact of CDSSs/KMSs on HCP satisfaction. These studies are summarized in Table H-7 of Appendix H. Of these 18 studies, 11 (61.1%) were conducted in the U.S.,^{34,51,52,58,91,98,100,105,107,150,153,154} 5 (27.8%) in Europe,^{39,66,67,80,99,126,127} 1 (5.6%) in multiple countries,²² and 1 (5.6%) location not reported.⁹³ Four of the studies (22.2%) were implemented in an academic setting,^{66,67,105,150,153,154} seven (38.9%) in a community setting,^{39,51,58,80,91,98,99} four (22.2%) in both academic and community settings,^{93,100,107,126,127} two (11.1%) in a VA setting,^{34,52} and one (5.6%) for which the setting was not reported.²² One study (5.6%) evaluated the systems in the inpatient environment,^{153,154} 13 (72.2%) in the ambulatory environment,^{39,51,52,58,80,91,98-100,105,107,126,127,150} 2 (11.1%) in both inpatient and ambulatory environments,^{34,93} 1 (5.6%) in the emergency department,^{66,67} and 1 (5.6%) for which the environment was not reported.²² Duration of the evaluation period across the studies ranged from 3 months²² to 4.5 years.³⁴ Eleven interventions (61.1%) were implemented using a system developed within the specific health care organization,^{34,39,52,80,91,98,105,107,126,127,150,153,154} 5 (27.8%) were implemented using a commercially available system,^{22,51,58,99,100} and 2 studies (11.1%) with a source that was not clearly described.^{66,67,93} Two systems (11.1%) aided health care providers with tasks for diagnosis,^{58,66,67} 7 (38.9%) for pharmacotherapy,^{34,91,93,100,105,107,126,127} 3 (16.7%) for chronic disease management,^{39,58,91} 3 (16.7%) for laboratory test ordering,^{51,52,107} 1 (5.6%) for initiating discussions with patients,⁸⁰ and 10 (55.6%) for additional clinical tasks.^{22,51,58,66,67,80,98,99,107,150,153,154} Fifteen of the systems (83.3%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{34,39,51,52,58,80,91,98-100,105,107,126,127,150,153,154} 1 (5.6%) delivered recommendations outside of the HCP-patient encounter,⁹³ and 2 studies (11.1%) did both.^{22,66,67} Five of the interventions (27.8%) required a mandatory response,^{22,51,66,67,91,100} 1 (5.6%) required the HCP to justify the reason for not complying with the recommendation,⁵² 5 (27.8%) did not have a response requirement,^{58,98,105,107,150} and in 7 studies (38.9%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{34,39,80,93,99,126,127,153,154} In 7 studies (3.9%), the recommendations were integrated within a CPOE or EHR,^{51,52,58,98,100,105,126,127} 3 (16.7%) were delivered via fax or computer printout,^{34,93,150} 3 (16.7%) via a standalone system,^{39,66,67,153,154} and 5 (27.8%) through other methods.^{22,80,91,99,107} The recommendations were automatically delivered to the HCP in 10 studies (55.6%);^{34,51,52,58,91,93,100,107,126,127,150} in 6 studies (33.3%), the HCP had to initiate an action to receive the recommendation,^{22,39,66,67,80,98,105} and in 2 studies (11.1%) the mode of access was not clearly described.^{99,153,154} Nine studies (50%) received a “Good” quality score,^{34,52,58,66,67,91,93,100,105,153,154} 6 (33.3%) had a “Fair” score,^{22,39,51,98,99,126,127} and 3 (16.7%) received a “Poor” score.^{80,107,150}

Two high-quality, recently published papers^{52,100} were examined in detail to guide observations about this group of studies. Fortuna et al. (2009)¹⁰⁰ evaluated the impact of hypnotic

prescribing recommendations on HCP satisfaction. They found that providers perceived that the reminders did not interfere with workflow (70%), provided useful evidence to support decisions (88%), provided useful education materials (83%), and increased awareness of costs (71%); however, 47% reported that the reminders prompted them to spend more time discussing treatment with patients. Sundaram et al. (2009)⁵² evaluated the impact of reminders for HIV risk assessment and testing onto HCP satisfaction. They reported that 61% of providers specifically described the clinical practice reminders to be “useful” in a postintervention survey.

From the research included in this section, we conclude that there is good evidence within the academic and community ambulatory settings that system-integrated, locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care and did not require a mandatory clinician response are well received by providers.^{22,51,52,58,66,67,91,93,98-100,105,107,126,127,150} However, only six of these studies included an evaluation period longer than 1 year^{34,51,91,99,100,105} and only two studies were evaluated with a sample size larger than 2000 patients.^{51,107}

HCP acceptance. We identified 22 of the 131 eligible studies (16.8%) that specifically examined the impact of CDSSs/KMSs on HCP acceptance. These studies are summarized in Table H-8 of Appendix H. Of these 22 studies, 15 (68.2%) were conducted in the U.S.,^{37,52,89,94,95,100,105,113,117,137,145,150,151,155,156} 5 (22.7%) in Europe,^{61,101-103,123,129} and 2 (9.1%) in Canada.^{54,108} Ten of the studies (45.5%) were implemented in an academic setting,^{37,94,95,105,117,137,145,150,155,156} 5 (22.7%) in a community setting,^{61,101-103,129,151} 2 (9.1%) in both academic and community settings,^{100,123} 2 (9.1%) in a VA setting,^{52,89} 1 (4.5%) in both academic and VA settings,¹¹³ and 2 (9.1%) for which the setting was not clearly described.^{54,108} Two studies (9.1%) evaluated the systems in the inpatient environment,^{117,145} 18 (81.8%) in the ambulatory environment,^{37,52,54,61,89,94,100-103,105,108,113,123,129,137,150,151,156} 1 (4.5%) in a long-term care facility,¹⁵⁵ and 1 (4.5%) in the emergency department.⁹⁵ Duration of the evaluation period across the studies ranged from 1 month¹²⁹ to 2.5 years.⁹⁵ Nineteen interventions (86.4%) were implemented using a system developed within the specific health care organization,^{37,52,54,61,89,94,95,101-103,105,108,113,117,123,129,145,150,151,155} 2 (9.1%) were implemented using a commercially available system,^{100,156} and 1 study (4.5%) did not clearly describe a source.¹³⁷ Two systems (9.1%) aided health care providers with tasks for diagnosis,^{145,156} 9 (40.9%) for pharmacotherapy,^{54,89,94,95,100,105,108,129,155} 5 (22.7%) for chronic disease management,^{61,94,101-103,123} 4 (18.2%) for laboratory test ordering,^{37,52,94,137} 1 (4.5%) for initiating discussions with patients,¹⁵¹ and 10 (45.5%) for additional clinical tasks.^{37,94,95,113,117,123,137,145,150,151} Nineteen of the systems (86.4%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{37,52,54,61,89,94,95,100-103,105,108,113,117,129,137,145,150,155} 2 (9.1%) delivered recommendations outside of the HCP-patient encounter,^{151,156} and 1 (4.5%) in both real time and outside of the HCP-patient encounter.¹²³ Four of the interventions (18.2%) required a mandatory response,^{95,100,145,156} 7 (31.8%) required the HCP to justify the reason for not complying with the recommendation,^{52,61,89,108,117,123,137} 3 (13.6%) did not have a response requirement,^{105,150,155} 1 (4.5%) required a noncommittal acknowledgement,⁹⁴ 1 (4.5%) required both a mandatory response and a reason for not complying,³⁷ and in 6 studies (27.3%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{54,94,101-103,113,129,151} In 11 studies (50%), the recommendations were integrated within a CPOE or EHR;^{52,54,95,100-103,105,108,117,145,155} 6 (27.3%) were delivered via fax or computer printout,^{37,89,94,137,150,151} 2 (9.1%) via a standalone system,^{61,129} and 3 (13.6%) had other formats

or combinations of formats.^{113,123,156} The recommendations were automatically delivered to the HCP in 17 studies (77.3%),^{37,52,54,61,89,94,95,100,108,113,117,129,137,150,151,155,156} and the HCP had to initiate an action to receive the recommendation in 5 studies (22.7%).^{101-103,105,123,145} Nine studies (40.9%) received a “Good” quality score,^{52,54,89,94,95,100,105,117,123} 10 (45.5%) had a “Fair” score,^{37,61,101-103,108,129,137,145,151,155} and 3 (13.6%) received a “Poor” score.^{113,150,156}

Three high-quality, recently published papers^{52,95,100} in which the CDSS interventions were thoroughly described were examined in detail to guide observations about this group of studies. Fortuna et al. (2009)¹⁰⁰ evaluated prescribing alerts for heavily marketed hypnotic medications on HCP acceptance. They found that only 23% of providers felt that recommendations that included alternative treatment suggestions and information on prescribing, patient education materials, and copayment for heavily marketed medications changed their prescribing decisions. Regarding HCP acceptance, the Sundaram et al. (2009)⁵² study found that providers were more likely to adhere to reminders to test for HIV rather than reminders to perform HIV risk assessment (11% versus 5%, $P < 0.01$). The reasons for not following recommendations due to lack of time or disagreement with the recommendation in general or for a specific patient visit decreased from the preintervention to postintervention survey although more clinicians reported an increase in the recommendation not being received concurrently with the patient visit during the postintervention survey. Terrell et al. (2009)⁹⁵ investigated prescribing alerts that targeted potentially inappropriately prescribed medications for elderly patients on 63 emergency department physicians for 2.5 years. They reported that providers accepted only 43% of the recommendations, which included recommendations for alternative treatment.

From the research included in this section, we conclude that evidence suggests that high levels of acceptance (at a rate greater than 75%) of recommendations from CDSSs that automatically delivered system-initiated (push) recommendations to providers are the exception^{129,156} rather than the rule. Most of the studies reported provider acceptance rates between 50% and 75% of locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care.^{61,101-103,117,129,150,151,156} However, only three of these studies included an evaluation period longer than 1 year and evaluated the decision support system with a sample size larger than 2000 patients.^{61,101-103} While representing only a limited subset of studies, in these studies there was no significant effect of a mandatory clinician response on provider acceptance.^{61,156} Three studies captured some of the reasons clinicians did not accept the recommendations, citing an anticoagulation scheduling interval not acceptable or a scheduling conflict for the recommended appointment,¹¹³ clinical judgment based on the patient’s medical history,⁸⁹ and lack of facilities to fulfill lifestyle and relaxation recommendations.¹²³

HCP use. We identified 15 of the 131 eligible studies (11.5%) that specifically examined the impact of CDSSs/KMSs on HCP use. These studies are summarized in Table H-9 of Appendix H. Of these 15 studies, 7 (46.7%)^{64,96-98,100,105-107} were conducted in the U.S.,^{3,8,25,29,41-44} 7 (46.7%) in Europe,^{4,29,99,101-104,109} and 1 (6.7%) in Canada.¹⁰⁸ One of the studies (6.7%) was implemented in an academic setting,¹⁰⁵ eight (53.3%) in a community setting,^{4,29,98,99,101-103,106,109} three (20%) in both academic and community settings,^{64,100,107} one (6.7%) in a VA setting,^{96,97} and two (13.3%) in settings that were not clearly described.^{104,108} All 15 studies (100%) evaluated the systems in the ambulatory environment.^{4,29,64,96-109} Duration of the evaluation period across the studies ranged from 6 months^{29,98,104,107,108} to 2 years.^{96,97,106} Eleven interventions (73.3%) were implemented using a system developed within the specific health

care organization,^{64,96-98,101-109} 3 (20%) were implemented using a commercially available system,^{4,99,100} and 1 (6.7%) had a source that was not clearly identified.²⁹ Three systems (20%) aided health care providers with tasks for diagnosis,^{64,104,106} 7 (46.7%) for pharmacotherapy,^{29,64,100,105-108} 5 (33.3%) for chronic disease management,^{4,64,96,97,101-103} 3 (20%) for laboratory test ordering,^{104,107,109} and 4 (26.7%) for additional clinical tasks.^{98,99,104,107} All 15 of the systems (100%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter.^{4,29,64,96-109} One of the interventions (6.7%) required a mandatory response,¹⁰⁰ one (6.7%) required the HCP to justify the reason for not complying with the recommendation,¹⁰⁸ four (26.7%) did not have a response requirement,^{98,105,107,109} and in nine studies (60%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{4,29,64,96,97,99,101-104,106} In 11 studies (73.3%), the recommendations were integrated within a CPOE or EHR;^{4,29,64,96-98,100-103,105,108,109} 1 (6.7%) was integrated within a CPOE or EHR and delivered via fax or computer printout,¹⁰⁷ 2 (13.3%) via a standalone system,^{104,106} and 1 study (6.7%) did not clearly describe how the CDSS was integrated.⁹⁹ The recommendations were automatically delivered to the HCP in six studies (40%),^{4,29,96,97,100,107,108} in seven studies (46.7%), the HCP had to initiate an action to receive the recommendation,^{98,101-106,109} one study (6.7%) delivered recommendations using both modes,⁶⁴ and one study (6.7%) had a mode that was not clearly described.⁹⁹ Five studies (33.3%) received a “Good” quality score,^{64,96,97,100,105,109} eight (53.3%) had a “Fair” score,^{4,29,98,99,101-103,106,108} and two (13.3%) received a “Poor” score.^{104,107}

Two high-quality, recently published papers^{96,97,100} were examined in detail to guide observations about this group of studies. Bosworth et al. (2005, 2009)^{96,97} evaluated prescribing reminders for antihypertensive medications and found that during the 2-year evaluation period in which the CDSS intervention was displayed, providers interacted with the intervention 57% of the time (n = 528 of 929). Regarding HCP use, Fortuna et al. (2009)¹⁰⁰ reported that during the 1-year evaluation period, hypnotic prescribing recommendations were seen at least once by only 89 of 257 (35%) of providers.

From the research included in this section, we conclude that relatively few studies actually assessed use of the CDSS. Among the studies that evaluated use within the ambulatory community setting of system-integrated CDSSs that provided recommendations synchronously at the point of care and did not require a mandatory clinician response, few documented use over 80%.^{29,109} Of these 2 studies, 62 providers were evaluated in the Van Wijk et al. (2001)¹⁰⁹ study for 12 months, and 300 providers were evaluated in the Filippi et al. (2003)²⁹ study for 6 months. Among studies evaluating clinical or economic outcomes, none of these studies demonstrated provider use of CDSSs greater than 80%.

Implementation of CDSSs/KMSs. Only 3 of the 131 eligible studies (2.3%) specifically examined the impact of CDSSs/KMSs on implementation in practice. These studies are summarized in Table H-10 of Appendix H. Of these 3 studies, 1 (33.3%) was conducted in the U.S.¹³³, 1 (33.3%) in Canada,⁷⁶ and 1 (33.3%) in both the U.S. and Canada.¹⁵⁷ Two of the studies (66.7%) were implemented in an academic setting^{133,157} and 1 (33.3%) in both academic and community settings.⁷⁶ One study (33.3%)¹⁵⁷ evaluated the systems in the inpatient environment and two (66.7%) in the ambulatory environment.^{76,133} Duration of the evaluation period across the studies ranged from 7 months⁷⁶ to 25 months.¹⁵⁷ All 3 interventions (100%) were implemented using a system developed within the specific health care organization.^{76,133,157} Two systems (66.7%) aided health care providers with tasks for diagnosis,^{76,157} 1 (33.3%) for

laboratory test ordering,⁷⁶ and 1 (33%) for additional clinical tasks.¹³³ All 3 (100%) systems delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter.^{76,133,157} One of the interventions (33.3%) did not have a response requirement,¹⁵⁷ 1 (33.3%) required a noncommittal acknowledgement,¹³³ and in 1 of the studies (33.3%), it was unclear to the abstractor if such requirement was present.⁷⁶ The recommendations were delivered online in 1 study (33.3%)¹³³ and 2 (66.7%) via a standalone system.^{76,157} In all 3 studies (100%), the HCP had to initiate an action to receive the recommendation.^{76,133,157} No studies received a “Good” quality score, 1 (33.3%) had a “Fair” score,¹⁵⁷ and 2 (66.7%) received a “Poor” score.^{76,133}

None of the 10 key papers reported data describing the impact of CDSSs on implementation. Of the studies that reported data for this outcome, the first found that a handheld decision support system at the point of care led to improvements in appropriate diagnostic management of angina, leading to an increase use of cardiac stress testing with the personal digital assistant compared to usual care (81% versus 50%).⁷⁶ Hamilton et al. (2004)¹⁵⁷ found that a standalone application that recorded the mother’s contractions and the baby’s heart rate and displayed a graph of the measured dilation led to decreased rates of caesarian sections at 6 months, from 19.54% in all eligible women in the year preceding the trial to 17.04% (P = 0.004), to 16.62% by 12 months (P = 0.00006) compared to the previous year. Flanagan et al. (1999)¹³³ reported that online immunization reminders aided clinicians in making appropriate immunization decisions and that those intervention sessions were significantly less likely to include a vaccination order.

We conclude that there is limited evidence that locally developed CDSSs that providers activate (pull) to receive decision support recommendations synchronously at the point of care will impact implementation.

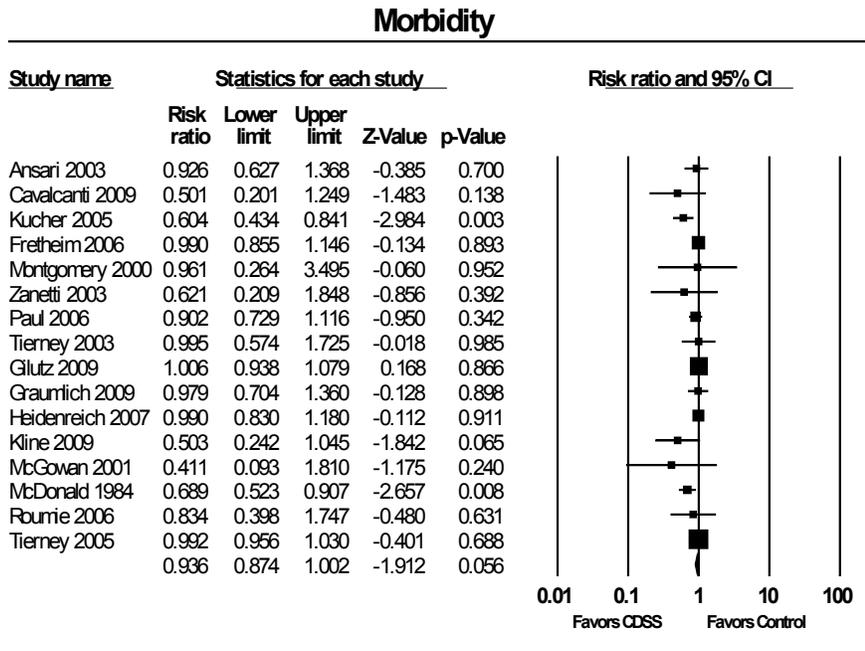
Impact on Clinical Outcomes

Morbidity. We identified 25 of the 131 eligible studies (19.1%) that specifically examined the impact of CDSSs/KMSs on morbidity. These studies are summarized in Table H-11 of Appendix H. Of these 25 studies, 15 (60%) were conducted in the U.S.,^{34,36,40,51,57,73,79,81,86,90-92,94,153,154,158} 7 (28%) in Europe,^{31,32,39,62,85,101-103,110,111} 1 (4%) in Brazil,¹⁵⁹ and 2 (8%) in multiple countries.^{44,157} Eleven of the studies (44%) were implemented in an academic setting,^{36,40,44,57,73,79,86,94,153,154,157,158} 9 (36%) in a community setting,^{31,32,39,51,62,85,91,101-103,110,111} 2 (8%) in both academic and community settings,^{90,159} and 3 (12%) in a VA setting.^{34,81,92} Six studies (24%) evaluated the systems in the inpatient environment,^{36,44,57,153,154,157,159} 17 (68%) in the ambulatory environment,^{31,32,39,40,51,62,73,79,81,85,86,90-92,94,101-103,110,111} 1 (4%) in both inpatient and ambulatory,³⁴ and 1(4%) in the emergency department.¹⁵⁸ Duration of the evaluation period across the studies ranged from 3 months⁵⁷ to 4.5 years.³⁴ Twenty-one interventions (84%) were implemented using a system developed within the specific health care organization,^{34,36,39,40,44,57,62,73,79,81,86,90-92,94,101-103,153,154,157-159} and 4 (16%) were implemented using a commercially available system.^{31,32,51,85,110,111} Four systems (16%) aided health care providers with tasks for diagnosis,^{44,85,157,158} 11 (44%) for pharmacotherapy,^{31,32,34,44,57,62,81,85,90,91,94,159} 13 (52%) for chronic disease management,^{39,62,73,79,81,86,90-92,94,101-103,110,111} 2 for laboratory test ordering,^{51,94} and 7 (28%) for additional clinical tasks.^{31,32,36,51,62,85,94,153,154} Twenty-one of the systems (84%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{31,32,34,36,39,44,51,57,73,79,81,86,91,92,94,101-103,110,111,153,154,157-159} 1 (4%) delivered

recommendations outside of the HCP-patient encounter,⁴⁰ and 3 (12%) were not clearly described.^{62,85,90} Five of the interventions (20%) required a mandatory response,^{36,51,57,91,110,111} 5 (20%) did not have a response requirement,^{31,32,44,92,157,158} 3 required a noncommittal acknowledgement,^{73,86,94} and in 12 studies (48%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{34,39,40,62,79,81,85,90,101-103,153,154,159} In 11 studies (44%), the recommendations were integrated within a CPOE or EHR,^{31,32,36,51,57,79,81,85,86,90,101-103} 6 (24%) were delivered via fax or computer printout,^{34,40,62,92,94,158} 6 (24%) via a standalone system,^{39,44,110,111,153,154,157,159} 1 (4%) was integrated within a CPOE or EHR and delivered via fax or computer printout,⁷³ and for 1 (4%), the recommendations were online and through email.⁹¹ The recommendations were automatically delivered to the HCP in 17 studies (68%),^{32,34,36,40,44,51,57,62,73,79,81,86,90-92,94,158} In 6 studies (24%), the HCP had to initiate an action to receive the recommendation,^{39,85,101-103,110,111,157} and in 2 studies (8%) the mode was not clearly described.^{153,154,159} Fourteen studies (56%) received a “Good” quality score,^{34,36,40,44,57,73,81,86,90,91,94,110,111,153,154,158} 9 (36%) had a “Fair” score,^{31,32,39,51,85,92,101-103,157,159} and 2 (8%) received a “Poor” score.^{62,79}

We conducted a meta-analysis of the effect of CDSSs on morbidity (Figure 6). Of the 25 studies, 15 (60%) provided the necessary endpoint data to be included in the meta-analysis.^{31,32,34,36,39,57,62,73,79,81,85,90,94,153,154,158,159} The combined relative risk of morbidity outcomes was 0.934 (95% CI 0.867 to 1.006). However, if the cardiovascular risk studies^{31,32,85} are eliminated (which are often not considered true measures of morbidity), the relative risk is 0.883 (95% CI 0.786 to 0.991).

Figure 6. Meta-analysis of Morbidity Outcomes



One high-quality, recently published paper^{110,111} was examined in detail to guide observations about this group of studies. Cleveringa et al. (2008, 2010)^{110,111} assessed a standalone decision support system designed to reduce cardiovascular risk for type 2 diabetic patients on morbidity. They found that the intervention group experienced an improvement in the 10-year coronary heart disease risk estimate of 1.4% (95% CI 0.3 to 2.6).

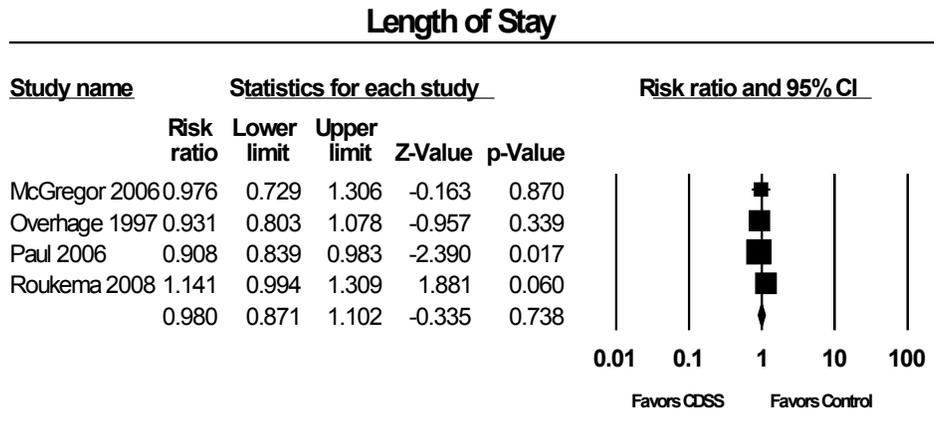
From the research included in this section, we conclude that there is modest evidence from the academic setting that locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care are effective at reducing the proportion of patients that are admitted or readmitted to the hospital or emergency department,^{40,62,94,158} or that experience a hypoglycemia episode,¹⁵⁹ or that have DVT or pulmonary embolism (PE) at 30 days.³⁶ This finding was supported by evidence from six studies that included evaluation periods of at least 1 year^{36,40,62,94,158,159} and from five studies with more than 2000 patients^{36,40,62,94}. In addition to the 6 studies that reported statistical significance, there is evidence that CDSSs that provided decision support recommendations synchronously at the point of care trend toward a reduction in morbidity. Examples of improved morbidity included a reduction in the proportion of patients that are admitted or readmitted to the hospital or emergency department,^{39,81,90,153,154} a lower coronary artery disease risk score for intervention patients,^{85,91,101-103,110,111} and a reduction in the number of patients that experience surgical site infections,⁵⁷ that have a shorter duration of fever,⁴⁴ or that have a colorectal adenoma detected.⁵¹ This supporting evidence was determined from seven studies that included evaluation periods of at least 1 year.^{51,81,91,101-103,110,111,153,154} While representing only a limited subset of studies, in these studies there was no significant effect of a mandatory clinician response on patient morbidity.

Length of stay. We identified 5 of the 131 eligible studies (3.8%) that specifically examined the impact of CDSSs/KMSs on length of stay. These studies are summarized in Table H-12 of Appendix H. Of these five studies, three (60%) were conducted in the U.S.,^{43,87,158} one (20%) in Europe,⁴⁸ and one (20%) in multiple countries.⁴⁴ Four of the studies (80%) were implemented in an academic setting,^{43,44,87,158} with one (20%) setting not reported.⁴⁸ Three studies (60%) evaluated the systems in the inpatient environment,^{43,44,87} and two (40%) in the emergency department.^{48,158} Duration of the evaluation period across the studies ranged from 12 weeks⁴³ to 2.3 years.⁴⁸ Four interventions (80%) were implemented using a system developed within the specific health care organization,^{44,48,87,158} and one (20%) was implemented using a commercially available system⁴³. Three systems (60%) aided health care providers with tasks for diagnosis,^{44,48,158} three (60%) for pharmacotherapy,^{43,44,87} and two (40%) for laboratory test ordering.^{48,87} All of the systems (100%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter.^{43,44,48,87,158} Two of the interventions (40%) did not have a response requirement,^{44,158} one (20%) required a noncommittal acknowledgement,⁸⁷ and in two studies (40%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{43,48} In three studies (60%), the recommendations were integrated within a CPOE or EHR;^{43,48,87} one (20%) was delivered via fax or computer printout¹⁵⁸ and one (20%) via a standalone system.⁴⁴ The recommendations were automatically delivered to the HCP in all of the studies.^{43,44,48,87,158} All five studies (100%) received a “Good” quality score.^{43,44,48,87,158}

We conducted a meta-analysis of the effect of CDSSs on length of stay (Figure 7). Of the five studies, four (80%) provided the necessary endpoint data to be included in meta-

analysis.^{43,44,48,87} The interventions included recommendations for appropriate antibiotic therapy,⁴³ guideline-based reminders for corollary orders,⁸⁷ diagnostic management of children with fever,⁴⁸ and risk assessment calculators for infection and antibiotic treatment recommendations.⁴⁴ The combined relative risk for all studies was 0.977 (CI 0.884 to 1.081). However, if the Roukema et al.⁴⁸ study, which was conducted in the pediatric population in the emergency department setting rather than the hospital setting, was excluded from the analysis, the combined relative risk for all studies was 0.917 (CI 0.856 to 0.983).

Figure 7. Meta-analysis of Length of Stay Outcomes



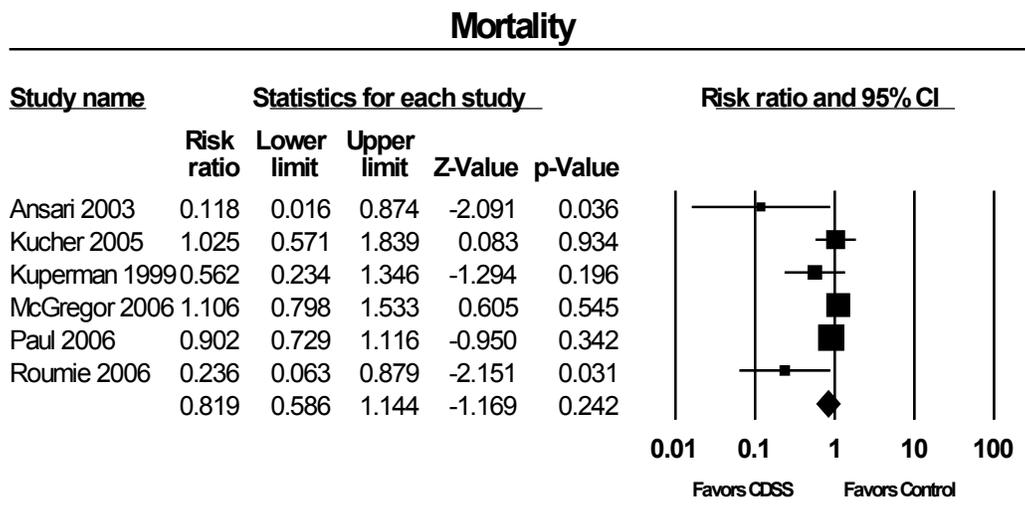
None of the 10 key papers reported data describing the impact of CDSSs on length of stay. Of the studies that reported data describing the impact of CDSSs on length of stay, one⁴⁴ evaluated a standalone system that focused on decreasing inappropriate antimicrobial use by recommending the three “best” antibiotic regimens in 2326 patients over 7 months and found that length of stay was lower in the intervention group (intervention: 6/8.83 [SD 11.29]; control: 6/9.45 [SD 11.52]; P = 0.055).

From the research included in this section, we conclude that there is limited evidence from the academic setting that CDSSs that automatically delivered system-initiated recommendations synchronously at the point of care trend toward reducing length of stay.^{43,44,87,158} This finding was supported by evidence collected from three studies that included more than 2000 patients;^{43,44,87} however, only one study¹⁵⁸ included an evaluation period longer than 1 year. While representing only a limited subset of studies, in these studies there was no effect of a mandatory clinician response on length of stay.

Mortality. We identified 6 of the 131 eligible studies (4.6%) that specifically examined the impact of CDSSs/KMSs on mortality. These studies are summarized in Table H-13 of Appendix H. Of these 6 studies, 5 (83.3%) were conducted in the U.S.^{36,43,81,90,114} and 1 (16.7%) in multiple countries.⁴⁴ Four of the studies (66.7%) were implemented in an academic setting,^{36,43,44,114} one (16.7%) in both academic and community settings,⁹⁰ and one (16.7%) in a VA setting.⁸¹ Four studies (66.7%) evaluated the systems in the inpatient environment^{36,43,44,114} and two (33.3%) in the ambulatory environment.^{81,90} Duration of the evaluation period across the studies ranged from 12 weeks⁴³ to 3 years and 4 months.³⁶ Five interventions (83.3%) were implemented using a system developed within the specific health care organization,^{36,44,81,90,114} and 1 (16.7%) was implemented using a commercially available system.⁴³ One system (16.7%) aided health care providers with tasks for diagnosis,⁴⁴ four (66.7%) for pharmacotherapy,^{43,44,81,90} two (33.3%) for chronic disease management,^{81,90} and two (33.3%) for additional clinical tasks.^{36,114} Five systems (83.3%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{36,43,44,81,114} with one system (16.7%) not clearly described.⁹⁰ Two of the interventions (33.3%) required a mandatory response,^{36,114} one (16.7%) did not have a response requirement,⁴⁴ and in three studies (50%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{43,81,90} In four studies (66.7%), the recommendations were integrated within a CPOE or EHR,^{36,43,81,90} one (16.7%) via a standalone system⁴⁴ and one (16.7%) delivered via pager and integrated within a CPOE or EHR.¹¹⁴ The recommendations were automatically delivered to the HCP in all six studies (100%).^{36,43,44,81,90,114} All six studies (100%) received a “Good” quality score.^{36,43,44,81,90,114}

We conducted a meta-analysis of the effect of CDSSs on mortality (Figure 8). The combined relative risk was 0.9048 (95% CI 0.7564 to 1.082). Thus, patients in the intervention group with a CDSS were 90% as likely to die as patients in the control group, and this combined effect did not reach statistical significance.

Figure 8. Meta-analysis of Mortality Outcomes



None of the 10 key papers reported data describing the impact of CDSSs on mortality. Of the studies that reported mortality data, one⁸¹ found that a system-integrated, locally developed CDSS designed to provide appropriate use of beta blockers for CHF patients was effective at reducing patient mortality by 12% (P = 0.05). This study⁸¹ was conducted in the ambulatory VA setting, and the intervention was evaluated for 1 year; however, the study only included 169 patients. The intervention automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care and did not require a mandatory clinician response. In addition to the one study that showed statistical significance, there is evidence that locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers demonstrated a trend toward reducing patient mortality.^{44,90,114} While representing only a limited subset of studies, in these studies there was no significant effect of a mandatory clinician response on mortality.

From the research included in this section, we conclude that limited evidence suggests that CDSS is effective at reducing patient mortality or demonstrating a trend toward reducing patient mortality.

Health care-related quality of life (HRQOL). We identified 5 of the 131 eligible studies (3.8%) that specifically examined the impact of CDSSs/KMSs on HRQOL or functional status. These studies are summarized in Table H-14 of Appendix H. Of these five studies, four (80%) were conducted in the U.S.^{73,79,86,92} and 1 (20%) in Europe.¹⁶⁰ Three of the studies (60%) were implemented in an academic setting,^{73,79,86} one (20%) in a community setting,¹⁶⁰ and one (20%) in a VA setting.⁹² All five studies (100%) evaluated the systems in the inpatient environment.^{73,79,86,92,160} Duration of the evaluation period across the studies ranged from 6 months¹⁶⁰ to 2 years and 4 months.^{73,79} All interventions (100%) were implemented using a system developed within the specific health care organization.^{73,79,86,92,160} Four systems (80%) aided health care providers with tasks for chronic disease management^{73,79,86,92} and one (20%) for additional clinical tasks.¹⁶⁰ Four of the systems (80%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{73,79,86,92} and 1 (20%) delivered recommendations outside of the HCP-patient encounter.¹⁶⁰ Two of the interventions (40%) did not have a response requirement,^{92,160} two (40%) required a noncommittal acknowledgement,^{73,86} and in one study (20%), it was unclear to the abstractor if such requirement was present.⁷⁹ In two studies (40%), the recommendations were integrated within a CPOE or EHR;^{79,86} two (40%) were delivered via fax or computer printout,^{92,160} and one (20%) was both within a CPOE or EHR and delivered via fax or computer printout.⁷³ The recommendations were automatically delivered to the HCP in all five studies (100%).^{73,79,86,92,160} Two studies (40%) received a “Good” quality score,^{73,86} two (40%) had a “Fair” score,^{92,160} and one (20%) received a “Poor” score.⁷⁹

None of the 10 key papers reported data describing the impact of CDSSs on HRQOL. Of the studies that reported HRQOL data, one reported that patients who received depression and anxiety treatment advice by intervention providers who utilized computer-based guidelines had significantly lower scores (a low score indicated better mental health) at 6 weeks ($P = 0.04$), but the significant effect was not maintained and at 6 months compared to usual care.¹⁶⁰ Murray et al. (2004)⁸⁶ found that patients who received care from intervention physicians who received evidence-based hypertension reminders had higher quality-of-life scores with the exception of the role of physician compared to those patients in the pharmacist intervention, dual-intervention, and control groups. Subramanian et al. (2004)⁹² reported that the intervention patients who were treated by providers who received evidence-based treatment suggestions for the treatment of heart failure had greater improvements in the mental component score and lower scores for the physical component scale compared to patients in the control group at 6 and 12 months. Tierney et al. (2003)⁷³ reported that intervention patients who were treated by physicians who received evidence-based cardiac care treatment suggestions for managing patients with heart disease had lower quality-of-life scores compared with the pharmacist intervention and control groups, with the exception of the mental health component, which was greater for the physician intervention group. An additional study by Tierney et al. (2005)⁷⁹ found that patients who were treated by physicians who received evidence-based treatment suggestions for asthma and chronic obstructive pulmonary disease (COPD) had greater quality-of-life scores for pain, general health, social function, and emotional subscales compared with the pharmacist intervention and control groups.

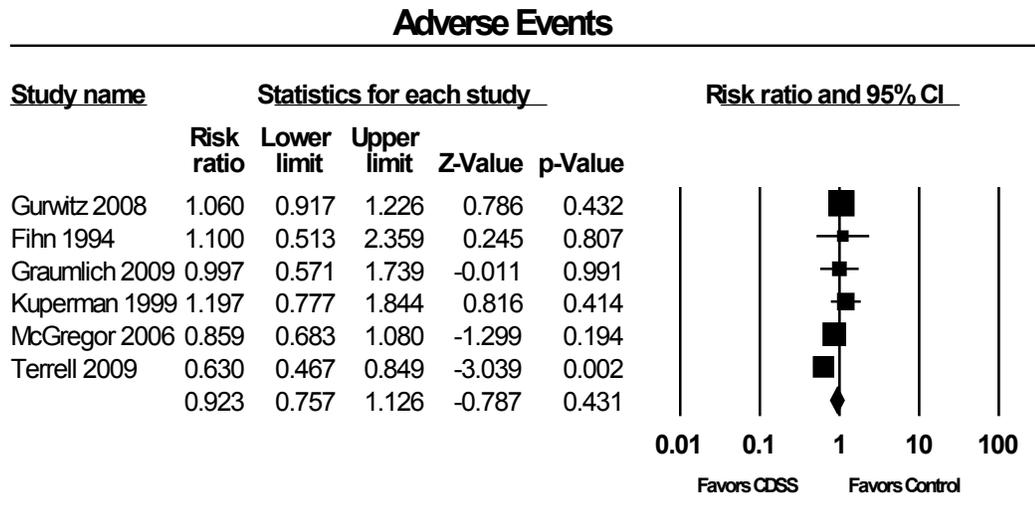
From the research included in this section, we conclude that there is limited evidence from the ambulatory setting that system-integrated, locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrate a trend toward higher quality-of-life scores.^{73,79,86,92,160} Notably, all of these

studies were evaluated with 500 to 1000 patients, and 4 were evaluated for a period longer than 1 year.^{73,79,86,92}

Adverse events. We identified 6 of the 131 eligible studies (4.6%) that specifically examined the impact of CDSSs/KMSs on adverse events. These studies are summarized in Table H-15 of Appendix H. Of these 6 studies, 5 (83.3%) were conducted in the U.S.,^{43,95,113,114,153,154} and one (16.7%) was conducted in multiple countries.¹⁶¹ Five of the studies (83.3%) were implemented in an academic setting,^{43,95,114,153,154,161} and one (16.7%) was in both academic and community settings.¹¹³ Three studies (50%) evaluated the systems in the inpatient environment,^{43,114,153,154} one (16.7%) in the ambulatory environment,¹¹³ one (16.7%) in a long-term facility,¹⁶¹ and one (16.7%) in the emergency department.⁹⁵ Duration of the evaluation period across the studies ranged from 12 weeks⁴³ to 2.5 years.⁹⁵ Five interventions (83.3%) were implemented using a system developed within the specific health care organization,^{95,113,114,153,154,161} and one (16.7%) was implemented using a commercially available system.⁴³ Three systems (50%) aided health care providers with tasks for pharmacotherapy^{43,95,161} and four (66.7%) for additional clinical tasks.^{95,113,114,153,154} Six systems (100%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter.^{43,95,113,114,153,154,161} Two of the interventions (33.3%) required a mandatory response,^{95,114} one (16.7%) did not have a response requirement,¹⁶¹ and in three studies (50%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{43,113,153,154} In three studies (50%), the recommendations were integrated within a CPOE or EHR,^{43,95,161} one (16.7%) was integrated within a CPOE or EHR and via pager,¹¹⁴ one (16.7%) via a standalone system,^{153,154} and one (16.7%) had a format that was not clearly described.¹¹³ The recommendations were automatically delivered to the HCP in four studies (66.7%),^{43,95,113,114} in one study (16.7%), the HCP had to initiate an action to receive the recommendation,¹⁶¹ and in one study (16.7%) the mode was not clearly described.^{153,154} Four studies (66.7%) received a “Good” quality score,^{43,95,114,153,154} one (16.7%) had a “Fair” score,¹⁶¹ and one (16.7%) received a “Poor” score.¹¹³

We conducted a meta-analysis of the effect of CDSSs on adverse events using the six studies (Figure 9). The combined relative risk was 0.923 (CI 0.770 to 1.107). Thus, patients in the intervention group with a CDSS were 92% as likely to experience an adverse event as patients in the control group and did not reach statistical significance.

Figure 9. Meta-analysis of Adverse Events



One high-quality, recently published paper⁹⁵ was examined in detail to guide observations about this group of studies. Terrell et al. (2009)⁹⁵ assessed prescribing alerts that targeted potentially inappropriately prescribed medications for elderly patients on adverse events in the emergency department and reported that there were significantly fewer inappropriate prescriptions in the intervention group compared to the control group (3.4% versus 5.4%) (P = 0.006; OR 0.59, 95% CI 0.41 to 0.85), with an absolute reduction of 2% (95% CI 0.7 to 3.3).

From the included evidence, we conclude that there is limited evidence from the academic setting that system-integrated CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrate an effect on reducing or preventing adverse events.

Impact on Relationship-centered Outcomes

Patient satisfaction. We identified 7 of the 131 eligible studies (5.3%) that specifically examined the impact of CDSSs/KMSs on patient satisfaction. These studies are summarized in Table H-16 of Appendix H. Of these seven studies, four (57.1%) were conducted in the U.S.,^{58,79,153,154,158} one (14.3%) in Europe,⁹⁹ one (14.3%) in Canada¹⁴⁰, and 1 (14.3%) did not report location.¹⁴⁹ Three of the studies (42.9%) were implemented in an academic setting,^{79,153,154,158} three (42.9%) in a community setting,^{58,99,140} and one (14.3%) did not report

the setting.¹⁴⁹ One study (14.3%) evaluated the systems in the inpatient environment,^{153,154} five in the ambulatory environment,^{58,79,99,140,149} and one (14.3%) in the emergency department.¹⁵⁸ Duration of the evaluation period across the studies ranged from 14 weeks¹⁴⁹ to 28 months.⁷⁹ Four interventions (57.1%) were implemented using a system developed within the specific health care organization^{79,149,153,154,158} two (28.6%) were implemented using a commercially available system,^{58,99} and one (14.3%) had a source that was not clearly described.¹⁴⁰ Two systems (28.6%) aided health care providers with tasks for diagnosis,^{58,158} two (28.6%) for chronic disease management,^{58,140} one (14.3%) for laboratory test ordering,¹⁴⁹ one (14.3%) for initiating discussions with patients,¹⁴⁰ and three (42.9%) for additional clinical tasks.^{58,99,153,154} All 7 of the systems (100%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter.^{58,79,99,140,149,153,154,158} Three of the interventions (42.9%) did not have a response requirement,^{58,149,158} and in four studies (57.1%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{79,99,140,153,154} In three studies (42.9%), the recommendations were integrated within a CPOE or EHR;^{58,79,149} one (14.3%) was delivered online,¹⁴⁰ one (14.3%) via a standalone system,^{153,154} one (14.3%) via fax or computer printout,¹⁵⁸ and one (14.3%) had a format that was not clearly described.⁹⁹ The recommendations were automatically delivered to the HCP in four studies (57.1%),^{58,79,149,158} and in three studies (42.9%) the mode was not clearly described.^{99,140,153,154} Four studies (57.1%) received a “Good” quality score,^{58,149,153,154,158} two (28.6%) had a “Fair” score,^{99,140} and one (14.3%) received a “Poor” score.⁷⁹

None of the 10 key papers reported data describing the impact of CDSSs on patient satisfaction. Of the studies that reported patient satisfaction data, one reported that patients who were treated by intervention providers who utilized a discharge planning application had a higher perception of discharge preparedness and satisfaction with medication information^{153,154}. Holbrook et al. (2009)¹⁴⁰ found that 75.9% of patients who received care from intervention providers who accessed a Web-based diabetes tracker to aid in therapeutic planning were more satisfied with the quality of their diabetes care. Kline et al. (2009)¹⁵⁸ reported that more intervention patients who were treated by intervention providers who received a printout of pretest probability of acute coronary syndrome were satisfied with the explanation of the medical problem than those patients in the control group. Feldstein et al. (2006)¹⁴⁹ found that patients who received a new study drug found baseline laboratory recommendations presented to patients through physician reminders during the patient visit, automated voice messages to the patient, and a call from a pharmacy team member all to be acceptable. Apkon et al. (2005)⁵⁸ reported that intervention patients who used problem-knowledge couplers to report their chief complaint and guide provider decisionmaking were less satisfied with the overall visit; however, intervention patients were more satisfied with the provider than those in the control group. An additional study by Tierney et al. (2005)⁷⁹ assessed patient satisfaction with the physician’s communication abilities and pharmacy and found there was no effect on patient satisfaction between those who were treated by intervention providers who received guideline-based recommendations for the management of asthma and COPD and those patients who were treated by control providers.

From the research included in this section, we conclude that there is conflicting evidence from studies with less than 1000 patients that CDSSs had a positive effect on patient satisfaction.^{140,149,153,154,158} While some studies did not find that provider use of CDSSs increased satisfaction with the care received or overall visit, there was evidence from studies with evaluation periods of at least 2 years that the intervention patients were more satisfied than those in the control group.

Impact on Workload and Efficiency

Number of patients seen/unit time. Of the eligible studies, none examined the impact of the CDSSs/KMSs on the number of patients seen/unit time.

Clinician workload. Of the eligible studies, none examined the impact of CDSSs/KMSs on clinician workload.

Efficiency. We identified 5 of the 131 eligible studies (3.8%) that specifically examined the impact of CDSSs/KMSs on efficiency. These studies are summarized in Table H-17 of Appendix H. Of these five studies, four (80%) were conducted in the U.S.,^{43,91,98,153,154} and one (20%) was conducted in multiple countries.²² Two of the studies (40%) were implemented in an academic setting,^{43,153,154} two (40%) in a community setting,^{91,98} and one (20%) did not report a specific setting.²² Two studies (40%) evaluated the systems in the inpatient environment,^{43,153,154} two (40%) in the ambulatory environment,^{91,98} and one (20%) did not report a specific environment.²² Duration of the evaluation period across the studies ranged from 12 weeks^{22,43} to 30 months.⁹¹ Three interventions (60%) were implemented using a system developed within the specific health care organization,^{91,98,153,154} and two (40%) were implemented using a commercially available system.^{22,43} Two systems (40%) aided health care providers with tasks for pharmacotherapy,^{43,91} one (20%) for chronic disease management,⁹¹ and three (60%) for additional clinical tasks.^{22,98,153,154} Four of the systems (80%) delivered recommendations in real time to enable decisionmaking during the HCP-patient encounter,^{43,91,98,153,154} and one (20%) delivered recommendations both in real time and outside of the HCP-patient encounter.²² Two of the interventions (40%) required a mandatory response,^{22,91} one (20%) did not have a response requirement,⁹⁸ and in two studies (40%), it was assumed that there was no user response requirement or it was unclear to the abstractor if such requirement was present.^{43,153,154} In two studies (40%), the recommendations were integrated within a CPOE or EHR;^{43,98} one (20%) was delivered online,²² one (20%) via a standalone system,^{153,154} and one (20%) was delivered online and via email.⁹¹ The recommendations were automatically delivered to the HCP in two studies (40%);^{43,91} in two studies (40%), the HCP had to initiate an action to receive the recommendation,^{22,98} and in one study (20%) the mode was not clearly described.^{153,154} Three studies (60%) received a “Good” quality score,^{43,91,153,154} two (40%) had a “Fair” score,^{22,98} and 0 received a “Poor” score.

None of the 10 key papers reported data describing the impact of CDSSs on efficiency. Of the studies that reported efficiency data, one reported that use of the KMS application that provided topic and nonspecific infobutton links to clinicians at the point of care significantly reduced the time that HCPs spent seeking information.⁹⁸ McGregor et al. (2006)⁴³ found that clinicians who received CDSS alerts spent less time resolving inappropriate antibiotic prescriptions in the intervention arm than the control arm of the trial. Alper et al. (2005)²² reported that the CDSS improved clinician efficiency in answering clinical questions using DynaMed when accessed during the HCP-patient encounter as well as outside of the encounter; however, the study also reported that system use did not improve time searching for information or time for unsuccessful searches. An additional study by Graumlich et al. (2009)^{153,154} reported that clinicians found the effort to use the intervention for discharge planning was more difficult than usual care (paper).

From the research included in this section, we conclude that there is limited evidence that CDSSs that provided decision support recommendations to providers synchronously at the point of care trended toward improvement in efficiency.^{22,43,98} This finding is supported by evidence from studies that included evaluation periods less than 6 months, although the McGregor article⁴³ reported that the study was discontinued at 12 weeks to implement the CDSS throughout the entire hospital based on the improved efficacy. Of note, only one of these studies evaluated the CDSS with more than 2000 patients.⁴³

Key Question 4

KQ 4: What generalizable knowledge can be integrated into electronic knowledge management and CDSSs to improve health care quality?

- 4a. Knowledge from published evidence about electronic knowledge management and CDSSs to improve health care quality based on different types of measures (health care process, relationship-centered, clinical, economic)
- 4b. How a clinician's expertise/proficiency/informatics competency in using the electronic knowledge management and CDSS affects clinical outcomes (one type of measure)

Key Points

- Multiple types of generalizable knowledge are incorporated into CDSSs. These include knowledge from the evidence base, knowledge that incorporates local context, and knowledge from various databases or repositories of medical information.
- Highly synthesized forms of generalized knowledge such as clinical guidelines and local adaptation of clinical guidelines (structured care protocols) are the most common types of generalized knowledge incorporated into CDSSs.
- A clinician's expertise/proficiency/informatics competency in using electronic knowledge management and CDSSs has not been evaluated systematically in the literature; evaluation of factors such as the clinician's expertise, acceptance, and usage of CDSSs should be part of the suite of outcomes used to measure the impact of CDSSs.

The Institute of Medicine's report "Crossing the Quality Chasm" identified the use of information technologies to support clinical decisionmaking as a critical strategy in translating medical research into clinical practice.¹⁶² (Interest in the use of these technologies reflects a growing understanding that there is often a gap between scientific knowledge about best care and its application to clinical practice.¹⁶³ The potential benefit of information technologies, and CDSSs in particular, lies in their ability to harness the vast and rapidly evolving medical knowledge base to deliver timely, contextually relevant, evidence-based information to health care providers that, when acted upon, can improve quality of care and patient outcomes. To deliver context-specific and patient-specific recommendations, however, medical declarative knowledge must be encoded into both human readable and machine-processable rules.

Accordingly, knowledge sources that are up to date, clinically valid, trusted by health care providers, and easily integrated into CDSSs are critical to the effective performance of CDSSs.

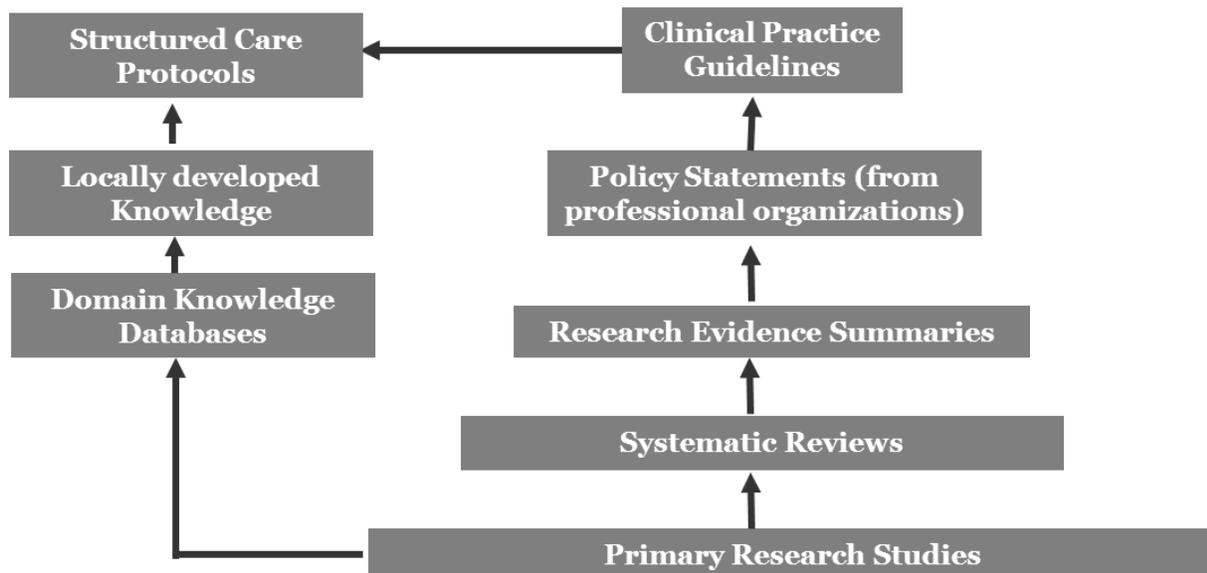
In this section of the report, we focus on the various types of generalizable knowledge integrated into CDSSs and found in the current evidence base. While acknowledging the diversity of systems, settings, decision tasks, designs, and contextual variables related to implementation and methodological quality represented by the studies in this report, we defined the primary purpose of this analysis to be exploratory and hypothesis generating.

Detailed Analysis

Using our 131 included RCT studies, we synthesized the published evidence to identify types and forms of generalizable knowledge that are integrated into CDSSs/KMSs with the aim of effecting improvements in health care quality. The types of generalizable knowledge identified were further categorized as either broad or targeted based on the scope and specificity of information delivered. For example, a CDSS that delivered evidence-based information related to a specific condition, clinical issue, or process of care was considered to be targeted in application whereas a CDSS that delivered evidence related to multiple conditions, clinical issues, or drug interactions was considered to be broad in scope and applicability. The purpose of the classification is to examine if the specificity of information delivered has a potential impact on provider acceptance and, therefore, the degree of use of these information technologies.

Generalizable knowledge incorporated into each of these studies was located on an evidence pyramid, a hierarchical organization of evidence in which each higher category is built on synthesis of evidence from the underlying categories (Figure 10).^{164,165}

Figure 10. Types of Generalized Knowledge Incorporated Into CDSSs/KMSs



These five categories, in increasing order of research synthesis from least synthesized to most synthesized, were:

1. **Primary research:** Knowledge from original studies in the primary literature. For the purpose of this review, specific health care protocols or algorithms derived from the primary literature would also constitute primary research.
2. **Systematic reviews and meta-analyses:** Investigations to synthesize the results of multiple primary investigations. Evidence derived from databases of systematic reviews compiled by organizations such as the Cochrane Collaboration and the Evidence-based Practice Centers supported by the Agency for Healthcare Research and Quality are also included in this category.
3. **Research evidence summaries:** Synthesis of systematic reviews and meta-analyses to develop summary of evidence for particular clinical circumstances.
4. **Policy statements:** Recommendations from professional organizations (e.g., American Heart Association) and national organizations such as Centers for Disease Control and Prevention and the U.S. Preventive Services Task Force.
5. **Clinical practice guidelines:** Include “systematically developed statements to assist practitioner and patient decisions about appropriate health care for specific clinical circumstances.”¹⁶²

CDSSs not only provide preappraised evidence-based knowledge (as in the categories above), but also harness patient-specific medical knowledge from drug databases or other electronic databases such as patient records, insurance databases, or institutional databases related to laboratory tests ordered/performed, drugs prescribed, or prescriptions filled. Additional sources of knowledge incorporated into CDSSs include knowledge from a local context or knowledge (protocols or algorithms) developed locally. An often-overlooked but key feature of the knowledge base incorporated into some CDSSs is local, patient-level data (e.g., all patients in a ward on antimicrobial therapy) that can then be combined with evidence-based knowledge (guidelines on antimicrobial use) to deliver patient-specific recommendations. We defined these types of generalized knowledge as structured care protocols—refinements of general guidelines or policy statements that reflect local context (local norms, practices, and practical constraints).

To accommodate these sources of knowledge, we added three categories of generalized knowledge of particular relevance to the design of CDSSs (for a total of eight categories). These were:

6. **Domain knowledge databases:** Repositories of domain-specific knowledge such as drug databases (Micromedex).
7. **Locally developed knowledge:** Evidence derived from the context of care, including collection of clinician and patient experiences. Typically, local knowledge is derived from data collected from local performance, planning, quality, outcome, and evaluation activity.¹⁶⁶⁻¹⁶⁸ Protocols, algorithms, or other forms of knowledge developed locally are also included in this category.
8. **Structured care protocols:** Local adaptation of clinical practice guidelines and other evidence-based knowledge. Structured care protocols incorporate knowledge such as local expertise (e.g., an expert panel of physicians at the local institution in which the intervention is implemented), patient-specific data drawn from various databases, and organized sources of clinical information such as online medical databases to realize forms of knowledge that are sensitive to and reflect local context or environment.

We used the above classification scheme to identify the source of generalized knowledge in each of the 131 articles included in the review. In addition, CDSSs employing forms of knowledge from multiple sources from any of the categories described above were noted as having multiple forms of generalized knowledge. The classification scheme employed was not meant to suggest a comprehensive set of categories with a rigid relationship between them; instead, the purpose was to highlight, for the convenience of the reader, particular categories suggested by the review of studies in this report, while acknowledging that other classification schemes, such as those discussed in Haynes (2007)¹⁶⁴ and Dicenso et al. (2009)¹⁶⁵ are possible.

We also abstracted data (when available) related to the clinician's proficiency/expertise in using CDSSs/KMSs; the purpose was to understand aspects of system-user interaction that have the potential to impact effectiveness of CDSSs. We interpreted the term "clinician expertise" broadly and included studies in this category as long as they provided some measure related to evaluation of the degree of familiarity/expertise of the clinician with the CDSSs.

Clinician proficiency/expertise was defined differently across the studies but included such metrics as length and type of training provided on the CDSS, clinician degree of familiarity with the CDSS, and clinician/institutional experience with electronic medical records/computerized order entry systems in which a CDSS was embedded. Details of the implementation and environment of the CDSS (e.g., whether embedded in a routinely used EHR system or introduced for the first time) provided additional contextual elements to interpret clinician expertise.

Based on reported provider expertise, we classified studies into the following categories:

- Studies reporting clinician expertise either directly or indirectly through measures such as length of training provided on a CDSS or clinician/institutional experience with electronic medical records/computerized order entry systems in which a CDSS was embedded.
- Studies that did not report clinician expertise.
- Studies in which the output of a CDSS was presented to the clinician in paper-based format obviating the need for interaction with the CDSS.

Results for Key Question 4a

The CDSSs/KMSs we evaluated in this review incorporated multiple types of generalized knowledge derived from the range of sources spanning the continuum of research evidence from primary studies and locally derived knowledge to domain knowledge databases and clinical guidelines. The various types of generalized knowledge incorporated into CDSSs are described in Table 11 with examples drawn from studies reviewed and the sources for the relevant included studies listed.

Table 11. Types and Sources of Generalizable Knowledge Incorporated Into CDSSs/KMSs

Type of generalizable knowledge	Number of studies (%)	Example studies	Description
Primary research Knowledge identified directly from original studies in the primary literature	3 (2.3)	Frame (1994) ¹⁵¹	Compliance with 11 health maintenance protocols identified in the literature
		Ornstein (1991) ¹³⁷	Recommendations for serum cholesterol measurements, fecal occult blood testing, mammography, Pap smears, and tetanus immunizations identified from the literature
		Stiell (2009) ¹⁴⁸	Canadian C-span Rule for selective ordering of cervical spine imaging
Systematic reviews Investigations to synthesize the results of multiple primary investigation	1 (0.8)	Christakis (2001) ¹¹²	Guidance derived primarily from systematic reviews integrated into CDSS to improve antibiotic prescribing practices for otitis media in children
Research evidence summaries Synthesis of systematic reviews and meta-analyses to develop summary of evidence for particular clinical circumstances	1 (0.8)	Alper (2005) ²²	Evaluation of Dynamed, an evidence synthesis tool that incorporates latest evidence from systematic reviews and primary research to deliver evidence summaries related to different clinic topics
Domain knowledge databases Repositories of domain specific knowledge such as Drug databases	1 (0.8)	Tamblyn (2008) ¹⁰⁸	Commercially available drug knowledge database (MentoR, Vigilance Sante, Montreal, Quebec) was integrated into CDSS to provide customizable alerts
Policy statements and recommendations (from professional and national organizations) Recommendations from professional organizations and National organizations	12 (9.2) ^a	McPhee (1989) ¹³⁶	American Cancer Society and National Cancer Institute guidelines for cancer screening
Clinical practice guidelines Systematically developed statements to assist practitioner and patient decisions about appropriate health care for specific clinical circumstances	33 (25.2) ^b	Bertoni (2009) ⁶⁸	National Cholesterol Education Program clinical practice guidelines

Type of generalizable knowledge	Number of studies (%)	Example studies	Description
Structured care protocols Local adaptation and synthesis of evidence based guidelines and other evidence-based knowledge to develop structured care protocols	60 (45.8) ^c	Judge (2006) ¹⁵⁵	CDSS was designed by a team of geriatricians, pharmacists, health services researchers, and information system professionals; team reviewed the types of preventable adverse events based on published research, and pharmaceutical drug interaction databases. Medications not on formulary at the facility and medications never used in elderly patients or long-term care setting were excluded.
Locally developed knowledge Protocols, algorithms, or other forms of knowledge developed locally	11 (8.4) ^d	Cavalcanti (2009) ¹⁵⁹	Locally developed protocol for maintaining blood glucose level between 100 and 130 mg/dL
		Hamilton (2004) ¹⁵⁷	Mathematical model for evaluating progress of labor in pregnant women
Databases/information Sources incorporating knowledge from multiple sources	9 (6.9) ^e	Apkon (2005) ⁵⁸	Knowledge database incorporating content from multiple sources including clinical textbooks, consensus reports, and clinical practice guidelines as well as consensus reports

a 29,41,42,50-52,61,71,90,118,132,134,136

b 4,24,31-34,39,55,56,60,62,64,65,68,74-76,79,84,86,89,96,97,99,101-103,110,111,116,121-124,141-143,156

c 23,25,26,28,36-38,44-47,53,57,66,67,69,70,72,73,77,78,80,83,85,87,88,91,92,94,95,100,104,106,107,109,115,117,119,120,124-127,131,133,135,138-140,144-147,149,150,152,155,158,159,161

d 27,30,35,48,49,113,114,128,129,153,154,157

e 22,40,43,54,58,63,82,93,98,105

Among the 131 studies evaluated in the review, the most common form of generalized knowledge incorporated into CDSSs was structured care protocols (60 studies, 45.1%); the second most common form was clinical practice guidelines (33 studies, 25.2%). In terms of the focus of the generalized knowledge, the majority of CDSSs (93 studies, 71%) incorporated targeted forms of knowledge (i.e., knowledge related to a specific guideline or medical condition); generalized knowledge dealing with multiple conditions and clinical situations was incorporated in 38 studies (29%).

Relationship of types of generalized knowledge to specific outcomes. We examined the relationship between the type of generalized knowledge incorporated into CDSSs and specific quality-of-care and patient outcomes. The outcomes evaluated were process outcomes (adherence/completion of recommended clinical study, preventive care or treatment), clinical outcomes (length of stay, morbidity, mortality, adverse events), and relationship-centered outcomes (HCP use).

Recommendations to order/complete a clinical study (clinical study adherence). We identified 24 of the 131 eligible studies (18.3%) that specifically examined the impact of CDSSs/KMSs on the ordering and completion of recommended clinical studies. These studies are summarized here, with details of the source and focus of the generalized knowledge provided in Table I-1 of Appendix I. The types of generalized knowledge used in these 24 CDSSs were primary research (4.2%), policy statements (12.5%), clinical practice guidelines (20.8%), structured care protocols (50%), locally developed knowledge (8.3%) and multiple types (4.2%). Generalized knowledge from systematic reviews, research evidence summaries, and domain knowledge databases was not employed in the CDSSs evaluated in these studies. Thus, most of the CDSSs incorporated evidence-based knowledge representing a high degree of evidence synthesis such as structured care protocols (50%), and clinical guidelines (20.8%). A notable exception was the CDSS developed by Steill et al. (2009)¹⁴⁸ for selective ordering of cervical spine imaging—the only system that used primary research, a less synthesized form of knowledge, as the source of generalized knowledge. In this study, the intervention group showed a relative reduction in cervical spine imaging of 12.8% (95% CI 9 to 16; 61.7 versus 53.3; $P = 0.01$) and the control group a relative increase of 12.5% (7 to 18; 52.8 versus 58.9; $P = 0.03$); changes were significant when both groups were compared ($P < 0.001$).

The majority of CDSSs reporting clinical study adherence incorporated knowledge that was targeted toward a particular condition or intervention (75%). A knowledge base that was broad and targeted multiple interventions/conditions was used in 6 (25%) CDSSs.

Recommendations to order/complete a preventive care service (preventive care adherence). We identified 40 of the 131 eligible studies (30.5%) that specifically examined the impact of CDSSs/KMSs on ordering or completing recommended preventive care services. These studies are summarized here, with details of the source and focus of the generalized knowledge provided in Table I-2 of Appendix I.

The types of generalized knowledge used in these 40 CDSSs were primary research (2.5%), policy statements (12.5%), clinical practice guidelines (32.5%), structured care protocols (47.5%), locally developed knowledge (2.5%) and multiple types (2.5%). Generalized knowledge from systematic reviews, research evidence summaries, or domain knowledge databases was not employed in the CDSSs evaluated in these studies. Thus, most of the CDSSs incorporated evidence-based knowledge representing a high degree of evidence synthesis such as

structured care protocols (47.5%), and clinical guidelines 32.5%. Of the 40 studies that addressed recommendations to order/complete preventive services, 29 (72.5%) were targeted toward a single condition/intervention while 11 studies (27.5%) incorporated knowledge that was broad in scope and addressed multiple conditions/intentions.

Recommendations to order/complete a specific treatment (treatment adherence). We identified 61 of the 131 eligible studies (46.6%) that specifically examined the impact of CDSSs/KMSs on the ordering and prescribing of therapy. These studies are summarized here, with details of the source and focus of the generalized knowledge provided in Table I-3 of Appendix I.

The types of generalized knowledge used in these 61 CDSSs were systematic reviews (1.6%), domain knowledge databases (1.6%), policy statements (6.6%), clinical practice guidelines (29.5%), structured care protocols (41%), locally developed knowledge (6.6%), and multiple types ((6.6%). Generalized knowledge from primary research and research evidence summaries was not employed in the CDSSs evaluated in these studies. Thus, most of the CDSSs incorporated evidence-based knowledge representing a high degree of evidence synthesis such as structured care protocols (29.5%) and clinical guidelines (41%).

Length of stay. We identified 5 of the 131 eligible studies (3.8%) that specifically examined the impact of CDSSs/KMSs on length of stay.^{43,44,48,87,158} These studies are summarized here, with details of the source and focus of the generalized knowledge provided in Table I-4 of Appendix I.

The types of generalized knowledge used in these five CDSSs were structured care protocols (60%), locally developed knowledge (20%), and multiple types (20%). Generalized knowledge from primary research, systematic reviews, research evidence summaries, domain knowledge databases, policy statements, or clinical practice guidelines was not employed in the CDSSs reporting length of stay. The majority of CDSSs reporting length of stay data incorporated knowledge that was targeted toward a particular condition or intervention (80%). The only study (20%) that employed generalized knowledge that was broad in scope was the one by Overhage et al. (1997)⁸⁷ that incorporated 22 preventive care measures for inpatients based on recommendations of the U.S. Preventive Services Task Force. However, use of CDSS, in this case, did not lead to significant decrease in length of stay. The average length of stay for intervention was 7.62 days, and for control was 8.12 days; difference of -0.5 days (95% CI -0.17 to 1.19; p = 0.94). Irrespective of the scope or the type of generalized knowledge, data from this small set of studies show limited effects of CDSSs on length of stay.

Morbidity. We identified 25 of the 131 eligible studies (19.1%) that specifically examined the impact of CDSSs/KMSs on morbidity. These studies are summarized here, with details of the source and focus of the generalized knowledge provided in Table I-5 of Appendix I.

The types of generalized knowledge used in these 25 CDSSs were policy statements (8%), clinical practice guidelines (40%), structured care protocols (40%), locally developed knowledge (8%), and multiple types (4%). Generalized knowledge from primary research, systematic reviews, research evidence summaries, or domain knowledge databases was not employed in the CDSSs evaluated in these studies. Thus, these CDSSs primarily employed knowledge representing a high degree of evidence synthesis. For example, Kucher et al. (2005)³⁶ used structured care protocols that combined local knowledge (derived from a patient database) and policy recommendations (North American and European consensus statements) and incorporated them in the form of a computer program linked to the patient database to identify hospitalized

patients at risk for DVT. Kucher et al. (2005)³⁶ reported that clinically diagnosed DVT or PE at 90 days occurred in 61 patients in the intervention group (4.9%) compared with 103 patients (8.2%) in the control group. The Kaplan-Meier estimates of the likelihood of freedom from DVT or PE at 90 days were 94.1% (95% CI 92.5 to 95.4%) and 90.6% (95% CI 88.7 to 92.2%), respectively ($p < 0.001$).

The majority of CDSSs reporting morbidity data incorporated knowledge that was targeted toward a particular condition or intervention (92%). Two studies employed knowledge that was broad in scope and addressed multiple conditions and drugs. Smith et al. (2008)⁹¹ developed an electronic library of messages using systematic reviews of the best available research on use of aspirin; use of ACE inhibitors and angiotensin receptor blockers; management of dyslipidemia, hypertension, chronic heart failure, and nicotine dependence; glycemic control; and diet and exercise. McDonald et al. (1984)⁹⁴ used a generalized knowledgebase consisting of 1491 physician-authored care rules that generated 751 different reminder messages addressing a variety of preventive care measures as well as treatments for acute conditions such as congestive heart failure.

Mortality. We identified 6 of the 131 eligible studies (4.6%) that specifically examined the impact of CDSSs/KMSs on mortality. These studies are summarized here, with details of the source and focus of the generalized knowledge provided in Table I-6 of Appendix I.

The types of generalized knowledge used in these six CDSSs were policy statements (16.7%), clinical practice guidelines (16.7%), structured care protocols (33.3%), locally developed knowledge (16.7%), and multiple types (16.7%). Generalized knowledge from primary research, systematic reviews, research evidence summaries, or domain knowledge databases was not employed in the CDSSs evaluated in these studies. The majority of CDSSs reporting mortality data incorporated knowledge that was targeted toward a particular condition or intervention (83.3%). For example, the generalized knowledge used in the CDSS evaluated by Ansari et al. (2003)⁸¹ was derived from guidelines on use of beta blockers for patients with chronic heart failure. Similarly, generalized knowledge used in the study by Roumie et al. (2006)⁹⁰ was derived from the Seventh Report of the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure. Structured care protocols in the form of a locally developed computer program that analyzed a patient database were used in a study by Kucher et al. (2005)³⁶ to identify hospitalized patients at increased risk of venous thromboembolism. The only study (16.7%) that employed generalized knowledge that was broad in scope was the one by Kuperman et al. (1999),¹¹⁴ in which the knowledge base consisted of 12 alerting rules that evaluated 12 conditions involving laboratory results and medications.

Of the studies that reported mortality data, only the one by Ansari et al. (2003)⁸¹ reported statistically significant results; deployment of a targeted CDSS incorporating generalized knowledge from guidelines on beta blockers for patients with chronic heart failure led to a reduction in patient mortality by 12% ($P = 0.05$). This study was conducted in the ambulatory VA setting, and the intervention was evaluated for 1 year; however, the study only included 169 patients. Based on the data reported in these studies, there is limited evidence for the effectiveness of CDSSs in reducing mortality.

Adverse events. We identified 6 of the 131 eligible studies (4.6%) that specifically examined the impact of CDSSs/KMSs on adverse events^{43,95,113,114,153,154,161}. These studies are summarized here, with details of the source and focus of the generalized knowledge provided in Table I-7 of Appendix I.

The types of generalized knowledge used in these six CDSSs were structured care protocols (33.3%), locally developed knowledge (50%) and multiple types (16.7%). Generalized knowledge from primary research, systematic reviews, research evidence summaries, domain knowledge databases, policy statements, and clinical practice guidelines were not employed in the CDSSs evaluated in these studies. In terms of focus, knowledge incorporated in these systems was broad in three of the six studies and targeted in two of the six studies. Among these six studies, significant risk reduction in adverse events was demonstrated in the study by Terrell et al. (2009),⁹⁵ which evaluated the utility of CDSSs in reducing prescription of potentially inappropriate medications to the elderly in an emergency department setting. Terrell et al. (2009) reported that intervention physicians prescribed one or more inappropriate medications during 2.6% of emergency department visits by seniors, compared with 3.9% of visits managed by control physicians ($p = 0.02$; odds ratio = 0.55, 95% CI 0.34 to 0.89).

The knowledge base for the CDSS used in this study was derived from a structured care protocol that was developed locally by an expert panel of two doctors of pharmacy, two physician information technology experts, three geriatricians, and three emergency physicians. The expert panel identified nine high-use, high-impact, potentially inappropriate medications by using the following sources of information medications on the Beers list; emergency department prescribing data from the preceding year, and medications on the formulary at the local institution. The form of generalized knowledge incorporated was considered broad in scope because it addressed multiple drugs (and conditions).

Impact on HCP use. We identified 15 of the 131 eligible studies (11.5%) that specifically examined the impact of CDSSs/KMSs on HCP use. These studies are summarized here, with details of the source and focus of the generalized knowledge provided in Table I-8 of Appendix I.

The types of generalized knowledge used in these 15 CDSSs were domain knowledge databases (6.7%), policy statements (13.3%) and clinical practice guidelines (40%), structured care protocols (26.6%), and multiple types (13.3%). Generalized knowledge from primary research, systematic reviews, research evidence summaries, or locally developed knowledge was not employed in the CDSSs evaluated in these studies. The majority of CDSSs incorporated knowledge that was targeted toward a particular condition or intervention (80%). For example, Bosworth et al.⁹⁶ used evidence-based guidelines for management of hypertension as the source of generalized knowledge incorporated into a CDSS and found during the 2-year evaluation period that the CDSS intervention was displayed, providers interacted with the intervention 57% of the time ($n = 528$ of 929). Fortuna et al.¹⁰⁰ targeted prescription of heavily marketed hypnotic medications with a CDSS that used knowledge from local pharmaceutical and therapeutics committee guidelines; however, during the 1-year evaluation period, recommendations regarding prescription of hypnotics were seen at least once by only 89 of 257 (35%) of providers.

CDSSs in which the knowledge incorporated was broad in scope (20%)^{98,105,108} harnessed information from multiple databases to provide context-specific information. These knowledge sources included a commercially available drug database (Mentor),¹⁰⁸ commercially available information databases (Micromedex, Skolar MD),¹⁰⁵ and information from multiple databases (Micromedex, UpToDate, MD consult Medline Plus).⁹⁸

Based on data reported in these studies, relatively few studies evaluated the relationship between use of CDSSs and the resulting outcomes; therefore, we were unable to draw any conclusions regarding the type of generalized knowledge and HCP use.

Discussion of Key Question 4a

In the continuum of evidence-based knowledge, both structured care protocols and clinical guidelines represent a high degree of evidence synthesis. The defining feature of structured care protocols is incorporation of local knowledge and the (often) participatory nature of the development that involves local practitioners. For example, in the study by Litzleman et al. (1993),³⁷ faculty consensus on guidelines from multiple sources was used to define preventive care protocols that took into consideration local practices, reimbursement, and practice constraints. Litzleman et al., report improved compliance among intervention physicians with preventive care reminders for fecal occult blood testing, mammography, and cervical Papanicolaou (Pap) testing (46% intervention versus 38% control; $p = 0.002$).

The collaborative process of development and incorporation of local knowledge should, in theory, lead to CDSSs that more accurately reflect the informational needs of clinicians. The impact of local adaptation and refinement of guidelines on clinical outcomes is a useful line of inquiry that should be explored further.

Results for Key Question 4b

Clinician expertise level was not reported in 46 of our 131 included studies

(35%).^{23,29,31,32,39,44,49,50,54,58,60,66-68,70,75-77,80-84,87,88,96,97,101-103,105,106,108,110-}

^{113,115,117,125,128,140,143,145,146,148,156,157,159,161}

CDSS recommendations were delivered using a paper-based format in 35 studies (27%); in these studies, clinician expertise in using a CDSS was not relevant to the eventual outcome since the clinicians interacted only with paper-based outputs of CDSSs.^{4,22,24,26-28,30,33,35,36,38,43,45-48,51-53,56,57,61,63-65,73,78,85,90,91,95,98-}

^{100,104,109,114,118,119,122,124,126,127,129,132,133,144,147,149,152-155}

Studies that provided data on clinical expertise (50 studies, 38%) often reported indirect measures such as type and length of training on CDSSs.^{4,22,24,26-28,30,33,35,36,43,45-48,51-53,56,57,61,63-65,78,85,90,91,95,98-100,104,109,114,118,119,122,124,126-}

^{128,132,133,144,147,149,152-155}

Among the 50 studies that reported clinicians' expertise, none of the studies directly examined the impact of their expertise in using the CDSS or related it to eventual clinical outcomes.

The reporting of clinician expertise in using CDSSs was highly variable across studies.

Clinician expertise ranged from highly trained and experienced users of the system^{35,155} to users who were new to the system^{22,104} or were provided some form of training on the system.¹³³

A particular distinction was between a CDSS implemented as an enhancement to an existing EHR system that had been in use for a certain length of time^{35,64} versus a CDSS deployed for the first time.⁵³ For example, in the study by Linder et al. (2009),⁶⁴ the decision support functionality was implemented as an enhancement to an EHR that had been in use for at least 4 years. In this case, training on the CDSS functionality only included an introductory email to clinicians, one practice visit by an investigator, and periodic emails to encourage use of the enhancements. Linder et al. evaluated tobacco treatment reminders in a primary care setting and reported improvements in the primary outcome of interest: the proportion of documented smokers who contacted a smoking cessation counselor (3.9% in intervention practices versus 0.3% in control practices, $p = 0.001$, 12,207 patients)

Tamblyn et al. (2003)⁵³ evaluated a CDSS that was introduced into practice for the first time and reported that clinicians' previous computer expertise influenced effectiveness of the CDSS. In this study, the potential of a CDSS to reduce inappropriate prescriptions to the elderly in a

primary care setting was evaluated. Tamblyn et al. (2003) reported that the CDSS was effective in reducing number of new, potentially inappropriate medications (RR 0.82, 95% CI 0.69 to 0.98), with a more selective effect on discontinuation of inappropriate prescriptions. In particular, clinicians' previous computer expertise was found to influence the effectiveness of the CDSS. The rate of initiation of inappropriate prescriptions among experienced computer users was 30% lower in the CDSS group than in the control group (RR 0.70, 95% CI 0.55 to 0.89). The rate of initiation of inappropriate prescriptions among computer beginners was identical in the CDSS and control groups (RR 1.03, 95% CI 0.82 to 1.29). In addition, clinicians reported technical hurdles related to implementation of the new CDSS, with 22% of the clinicians reporting frequent software and hardware problems in the first few months of the study that affected the degree of use of the CDSS.

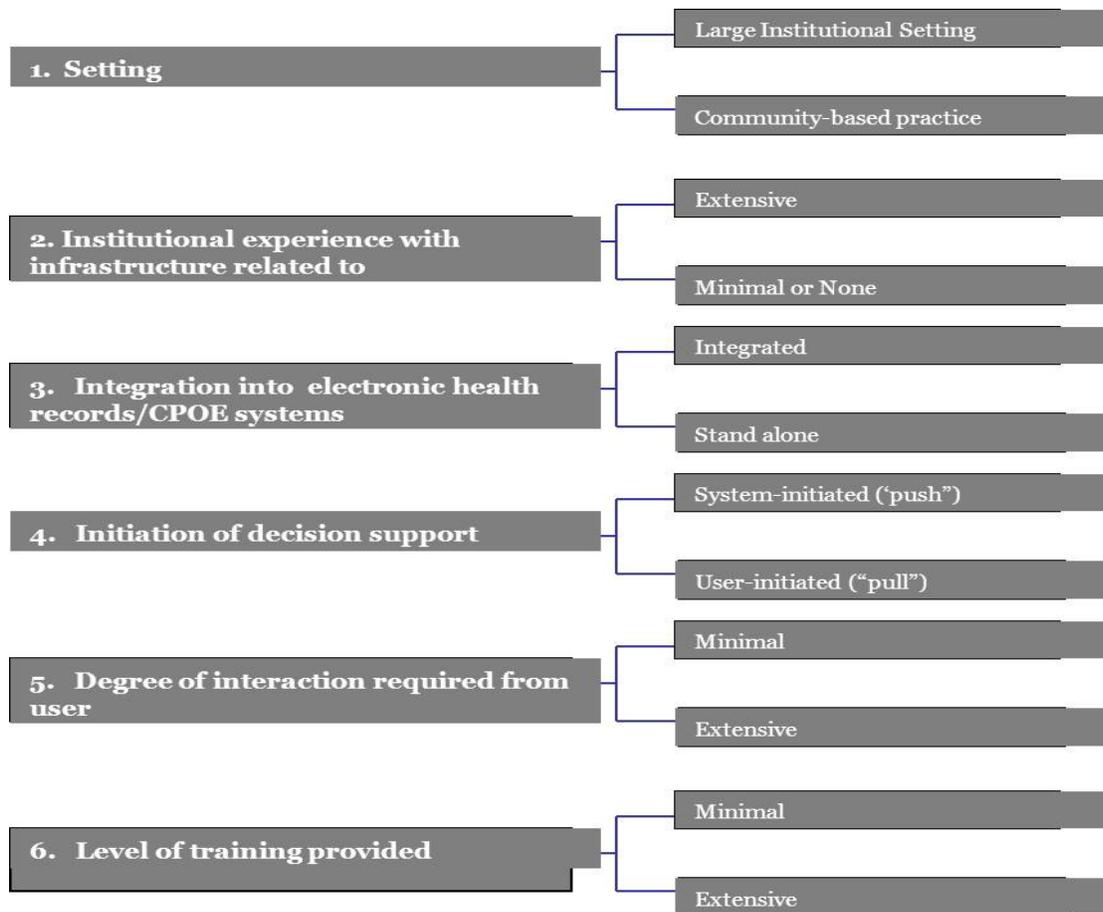
The degree of training provided on CDSSs varied across studies, ranging from a 1-hour tutorial and assistance during the first month of use¹³³ to a half-day training session and site visits by study authors.¹²² In addition, some studies required the use of a particular electronic medical record system as an inclusion criterion.^{85,127,144} In these studies, it was reasonable to assume that the CDSS was implemented as an additional functionality in a routinely used system.

Discussion of Key Question 4b

A causal relationship between clinicians' expertise in using CDSSs and successful implementation of CDSSs as reflected in improvement in the quality of care (process and clinical outcomes) could not be established based on data from the studies reviewed. In the absence of directly relevant data, we examined the context in which clinicians' expertise operated as a variable with influence on the effectiveness of CDSSs and potential impact on patient outcomes. CDSSs/KMSs evaluated as part of this review were diverse in the types of tasks performed as well as the settings in which they were employed; therefore, clinicians' expertise as a variable may not hold the same level of significance across systems and study settings. For example, in evaluating the role of clinicians' expertise, CDSSs integrated into well-established EHR or CPOE systems are necessarily different from those being introduced into practice for the first time. CDSSs built into existing EHR systems and implemented at large institutions with longstanding experience in using EHRs may present a far less steep learning curve compared to systems being introduced for the first time. In particular, a CDSS implemented as an alert or as a reminder embedded in the EHR only represents an additional functionality in a routinely used and familiar EHR system. The key challenge to CDSS success in such cases may be drawing clinicians' attention to the functionality represented by the CDSS and monitoring clinician acceptance and usage of the CDSS/KMS. On the other hand, in case of a CDSS/KMS implemented in settings with no prior institutional experience in the use of computerized records, clinicians' acceptance and expertise may play a more important role. In particular, clinicians' expertise or lack thereof may be more significant when a CDSS is implemented in small, community-based practices with no institutional experience in using computerized records. System functionality, complexity, and design attributes have the potential to modify the influence of clinicians' expertise. In this context, a clear distinction may be made between systems in which information is presented automatically as part of the workflow without the need for additional input from the clinician and those who require the clinicians to seek out the information. Clinicians' expertise/familiarity with CDSSs might be less significant when evaluating CDSS designs that do not require active information-seeking behaviors or additional

steps in the workflow. Factors that potentially modify clinicians' expertise with CDSSs are shown in Figure 11.

Figure 11. Contextual Factors That May Impact/Mediate Role of Clinician's Expertise



These include factors related to the environment in which CDSSs are implemented (setting, institutional experience) as well as specific features related to the design of CDSSs (degree of integration into existing computerized record systems, system-initiated or clinician-initiated provision of decision support, degree of interaction required from user and the level of training provided).^{5,9} These proposed factors do not constitute an exhaustive list but should be considered as possible candidate factors for evaluation. Future research could address how these and other contextual variables influence clinicians' expertise and acceptance of CDSSs and impact clinical outcomes.

In summary, the role of clinicians' expertise with a CDSS/KMS and its effect on clinical outcomes can be examined only in the larger context of CDSS functionality and the setting in which it is implemented. It may very well be that clinicians' expertise is a necessary but not sufficient causal factor in determining the effectiveness of CDSSs and eventual patient outcomes. Examining the role of clinicians' expertise (and its evolution over time) should be part of the suite of user-system interaction factors reported in studies of CDS. In the vast majority of

studies evaluated as part of this review, the objective of the CDSS was to enable changes in clinician behavior and improve the quality of care delivered. It stands to reason that system-user interaction features such as expertise, familiarity, acceptance, and degree of usage are important to the success or failure of the CDSS.^{6,169} Focusing greater scrutiny on user-related features can help us understand the specific conditions under which CDSS are effective and contribute to improvements in health care quality that are reflected in better patient outcomes.

Future Research

Studies of CDSSs using RCTs should include a qualitative component, geared toward answering the question, What worked and what didn't work in the implementation of CDSSs? For example, in evaluation of CDSSs geared toward improving guideline adherence, clinician attitudes toward specific guidelines being implemented and factors such as practical constraints affecting guideline adherence should be explored. This analytic approach will set the stage for designing CDSSs that not only meet the specific informational needs of clinicians' but, more crucially, help us determine what improvements in practice can be addressed with CDSSs and isolate these improvements from other determinants of clinical practice that lie outside the scope of CDSSs.

The full suite of outcomes used to measure the impact of CDSSs should include a robust evaluation of factors related to the clinician-system interaction. Ultimately, even the most sophisticated CDSSs can influence clinical practice only when they are accepted, deemed to be useful by the end user, and effectively implemented in practice. We recommend additional studies that examine the influence of provider expertise on clinical as well as process outcomes.

Summary and Discussion

For this report, we conducted a systematic review of the indexed medical literature to identify the best evidence concerning the impact of clinical decision support and knowledge management systems (CDSSs/KMSs) on a broad set of outcomes. We also sought to identify gaps in the available evidence about the effectiveness of CDSSs/KMSs. We screened 13,752 abstracts and manuscripts dating to 1976, from which we identified 274 comparative studies—of which 131 were RCTs. All of the RCTs were abstracted to evidence tables (Appendix D) that supplied the data for this report. Studies with similar outcomes and common endpoints were combined to conduct meta-analyses. This review investigated the continuum of information support for clinical care, including traditional CDSSs as well as information retrieval systems and knowledge resources developed for access at the point of care.

Of the three study designs used to assess CDSSs/KMSs, the most common approach was RCTs followed by quasi-experimental studies and observational studies. The most common outcomes assessed were process measures across all study designs followed by usability assessments and clinical outcomes. Over the past 5 years, the number of RCTs focusing on clinical outcomes in nonacademic settings using commercially developed CDSSs has increased; however, the majority of included studies still reported about locally developed systems in ambulatory care settings that provided clinical decision support for physicians on a single or limited set of conditions.

Using meta-analysis on studies that evaluated adherence to preventive care, clinical study, and treatment as an outcome, we confirmed 3 previously reported features associated with successful CDSS implementations⁹ and identified 4 additional features. These seven features included **general system features**: integration with charting or order entry system to support workflow integration (new); **clinician-system interaction features**: automatic provision of decision support as part of clinician workflow (previous), no need for additional clinician data entry (new), and provision of decision support at the time and location of decisionmaking (previous); **communication content features**: provision of a recommendation, not just an assessment (previous), and promotion of action rather than inaction (new); and **auxiliary features**: local user involvement in development process (new). These features were present across the breadth of CDSS implementations in diverse venues (multiple countries, inpatient and ambulatory environments, academic and community settings) using both locally and commercially developed systems.

With regard to outcomes, we discovered strong evidence that CDSSs that include the above features favorably impact care processes including prescribing treatments, facilitating preventive care services, and ordering clinical studies. This effect on processes spanned diverse venues and systems. In contrast to previous observations, where most reports of successful clinical decision support implementation were based on locally developed systems at four sites,³ this effect has now been observed at diverse community sites using commercially developed systems. We found, however, that evidence demonstrating positive effects of clinical decision support on clinical and economic outcomes remains limited. We also found limited evidence showing an impact of clinical decision support on clinical workload and efficiency.

The predominant source of knowledge used in CDSSs was derived from structured care protocols and clinical practice guidelines that focused on a single or limited set of medical conditions. Local adoption of general knowledge sources was common. We found scant evidence

exploring the relationship of clinicians' expertise and the successful implementation of clinical decision support. In spite of a favorable trend to fill a gap identified in a previous evidence report that studied commercial CDSSs/KMSs in community settings,³ the literature is still lacking for evidence concerning the content of CDSSs, the recipients of clinical decision support, the types of outcomes reported in CDSS evaluations, and the issues related to implementation and deployment of CDSSs to support wide-scale application as expected for the meaningful use of EHRs.

Most of the published RCTs on CDSSs focused on a single or limited set of conditions. Studies are needed to determine how clinical decision support can be provided for multiple health issues simultaneously. Such studies will need to address reconciliation of advice across diverse combinations of comorbid conditions, prioritization of recommendations, and avoidance of "alert fatigue." In a second issue related to CDSS/KMS content, we found a paucity of studies on KMS (only two RCTs identified). Accordingly, studies need to be initiated to generate rigorous evidence to determine how information retrieval systems and point-of-care knowledge resources can most effectively be used to improve health care.

With regard to the recipients of clinical decision support, most studies concentrated on decision support delivered to physicians. As health care migrates to more team-oriented delivery models, future studies will need to investigate which care team members should receive clinical decision support advice to optimize effectiveness.

In the area of outcomes, relatively few studies reported clinical outcomes, and even fewer addressed the cost implications of clinical decision support. Outcome studies that explored the unintended consequences of decision support were also limited.

Finally, with regard to deficiencies in the best literature, we discovered relatively few RCTs that rigorously evaluated issues related to CDSS implementation, workflow, and the delivery of care. In a similar vein, we found few studies that investigated how CDSSs could be effectively ported to different settings. Most of the reports focused on the use of a CDSS at a single institution or closely related institutions. The portability issue will need to accommodate the discovery that user involvement in CDSS development is a feature associated with successful implementation.

Limitations of This Review

Our systematic review has several limitations. First, we acknowledge a publication bias in that studies with positive outcomes are more likely than negative studies to be reported in the medical literature. Accordingly, the literature favors features that lead to CDSS success and may underreport features that resulted in CDSS implementation failures. A second limitation of the literature on clinical decision support is that the studies are extremely heterogeneous with regard to the systems, populations, settings, and outcomes. Consequently, it is difficult to derive general observations about CDSSs since each system and setting has unique characteristics that may be critical but not identified or transferable. We sought to minimize this limitation in our meta-analysis by including studies with a common endpoint within the outcome categories; still, it was difficult to isolate the effect of individual factors or features. A third limitation is that we chose to concentrate primarily on RCTs for the bulk of the evidence for this report and thus excluded findings from quasi-experimental and observational studies. While RCTs provide the best evidence on CDSS effectiveness, these RCTs may provide less information regarding issues related to CDSS implementation, impact on workflow, and factors affecting usability. A fourth

limitation is related to the variable descriptions of intervention details provided in each publication. We abstracted specific data, pertaining to the design and user interaction with each system, that were commonly reported within informatics journal publications but which were less frequently described in clinically oriented publications. Conceivably, some studies did not report detailed system descriptions due to article length restrictions.

To frame the context for the relevance of this report, we highlight the increasing political interest and financial investment of the U.S. government in resources for health information technology. The meaningful use of CDSSs/KMSs needs to be objectively informed regarding the role that CDSSs/KMSs can and should play in the reshaping of health care delivery. Stage 1 meaningful use guidelines¹ specify the implementation of a single clinical decision support rule. Ensuring successful CDSS implementation across the national landscape and preparing for the subsequent rounds of meaningful use standards is no longer just about getting the “right” information to the “right” person. Moving clinical decision support from isolated implementations at well-established institutions to broad penetration will require a better understanding of what the right information is and when and how it is delivered to the right person.

Ideally, the requirements for Stages 2 and 3 need to be more direct and based on demonstrated evidence of clinical effectiveness of CDSS tools. For example, a recent summary report has identified the lack of integration of health information technology into clinician workflow in a meaningful way as a potential contributor for the mixed success of clinical decision support.¹⁷⁰ It follows, therefore, that further understanding is needed about when to provide decision support that fits into clinician workflow and workload and how such support translates into provider acceptance, satisfaction, and improved quality of care. Another gap we identified from the included evidence that may have consequences for the meaningful use of clinical decision support is how to best present the knowledge to providers.

Conclusions

This systematic review has provided solid evidence that CDSSs can improve process measures in inpatient and ambulatory care settings with both commercially and locally developed systems in both academic and community environments in multiple countries for a single or a limited set of conditions. Table 12 summarizes the key points for each key question and provides a grade for the level of supporting evidence. In addition, seven factors/features of CDSSs have been identified that correlate with a successful clinical decision support implementation. These features address how a CDSS is integrated with other systems, how clinicians should interact with a CDSS, how content should be communicated to CDSS users, how periodic performance feedback supports CDSSs, and how intended users should be involved in CDSS development.

The evidence analyzed in this review builds upon an earlier review by Chaudhry et al. (2006)³ in that the benefits of CDSSs have now been consistently demonstrated using commercially developed CDSSs outside of four experienced academic centers with locally developed systems. In spite of these advances in the field, significant research is still required to promote the widespread use of CDSSs and to augment the clinical effectiveness of CDSSs. This research should investigate (1) how to expand CDSS content to accommodate multiple comorbid

conditions simultaneously, (2) which members of the care team should receive clinical decision support, (3) what impact CDSSs have on clinical and economic outcomes, and (4) how CDSSs can be most effectively integrated into workflow and deployed across multiple diverse settings. Further understanding of CDSSs is increasingly important in order to optimally define the role of CDSSs in the context of meaningful use for EHRs.

Table 12. Summary of Key Findings

Key Question	Level of Evidence	Conclusions
<p>Key Question 1: What evidence-based study designs can be used to determine the clinical effectiveness of CDSSs?</p>	<p>High</p>	<ul style="list-style-type: none"> • 264 studies were reviewed including 131 RCTs (49.6%), 99 quasi-experimental (37.5%), and 34 observational studies (12.9%) • Clinical and health care process outcomes were frequently reported in all three study design types: <ul style="list-style-type: none"> ○ Clinical outcomes (25.2% of RCTs, 31.3% of quasi-experimental, and 38.2% of observational studies) ○ Health care process outcomes (87.0% of RCTs, 73.7% of quasi-experimental, 67.6% for observational studies) • When RCT studies are impractical to conduct, well-designed quasi-experimental and observational studies can be used to evaluate the clinical effectiveness of CDSS.
<p>Key Question 2: What contextual factors/features influence the implementation and use of electronic knowledge management and CDSSs?</p>	<p>Moderate</p>	<ul style="list-style-type: none"> • Using meta-analysis on studies that evaluated adherence to preventative care (22 studies), clinical study (17 studies), and treatment as an outcome (39 studies), we confirmed 3 previously reported features associated with successful CDSS implementation and identified 4 additional features. • Our meta-analysis confirmed 3 previously reported factors/features were strongly associated with successful CDSS implementation: <ul style="list-style-type: none"> ○ Automatic provision of decision support as part of clinician workflow (OR of 1.38, 95 CI of 1.13 to 1.68 for adherence to preventive care, OR of 2.05, 95 CI of 1.53 to 2.73 for ordering of clinical studies, OR of 1.55, 95 CI of 1.24 to 1.95 for prescribing or ordering of therapy) ○ Provision of decision support at time and location of decisionmaking (OR of 1.39, 95 CI of 1.17 to 1.65 for adherence to preventive care, OR of 2.09, 95 CI of 1.42 to 3.06 for ordering of clinical studies, OR of 1.72, 95 CI of 1.37 to 2.14 for prescribing or ordering of therapy) ○ Provision of a recommendation, not just an assessment (OR of 1.41, 95 CI of 1.11 to 1.80 for adherence to preventive care, OR of 2.49, 95 CI of 1.70 to 3.63 for ordering of clinical studies, OR of 1.61, 95 CI of 1.25 to 2.06 for prescribing or ordering of therapy) • The meta-analysis also identified 4 additional factors/features that were correlated with the success of CDSSs:

Key Question	Level of Evidence	Conclusions
		<ul style="list-style-type: none"> ○ Integration with charting or order entry system to support workflow integration (OR of 1.48, 95 CI of 1.06 to 2.06 for adherence to preventive care, OR of 1.67, 95 CI of 1.49 to 2.81 for ordering of clinical studies, OR of 1.61, 95 CI of 1.28 to 2.03 for prescribing or ordering of therapy) ○ Promotion of action rather than inaction (OR of 1.28, 95 CI of 1.08 to 1.52 for adherence to preventive care, OR of 1.64, 95 CI of 1.25 to 2.16 for ordering of clinical studies, OR of 1.56, 95 CI of 1.18 to 2.07 for prescribing or ordering of therapy) ○ No need for additional clinician data entry (OR of 1.41, 95 CI of 1.08 to 1.84 for adherence to preventive care, OR of 1.71, 95 CI of 1.25 to 2.35 for ordering of clinical studies, OR of 1.71, 95 CI of 1.30 to 2.26 for prescribing or ordering of therapy) ○ Local user involvement in development process (OR of 1.49, 95 CI of 1.13 to 1.95 for adherence to preventive care, OR of 1.91, 95 CI of 1.12 to 3.04 for ordering of clinical studies, OR of 1.98, 95 CI of 1.40 to 2.78 for prescribing or ordering of therapy) <ul style="list-style-type: none"> ● Many of the studies included more than one feature/factor and because the studies did not specifically evaluate whether the systems with and without an individual factor/feature differed in terms of their impact on the outcome of interest, it is difficult to determine the importance of individual factors/features.
Key Question 3: What is the impact of introducing electronic knowledge management and CDSSs?		
(a) Changes in the organization of health care delivery	Insufficient	<ul style="list-style-type: none"> ● Of the eligible studies, none examined the impact of CDSSs/KMSs on changes in the organization of health care delivery.
(b) Changes in the workload and efficiency for the user		
a. Number of patients seen/unit time	Insufficient	<ul style="list-style-type: none"> ● Of the eligible studies, none examined the impact of CDSSs/KMSs on the number of patients seen/unit time.
b. Clinician workload	Insufficient	<ul style="list-style-type: none"> ● Of the eligible studies, none examined the impact of CDSSs/KMSs on clinician workload.
c. Efficiency	Insufficient	<ul style="list-style-type: none"> ● We included 5 studies (3.8%) (including three good-quality studies) that examined the impact of CDSSs/KMSs on efficiency. ● From these studies there is limited evidence that CDSSs that provided decision

Key Question	Level of Evidence	Conclusions
		support recommendations to providers synchronously at the point of care trended toward improvement in efficiency.
(c) Changes in process and clinical outcomes		
<i>Process outcomes:</i>		
a. Recommended preventative care service ordered/completed	High	<ul style="list-style-type: none"> • 40 of our included studies (30.5%) examined the impact of CDSSs/KMSs on ordering or completing recommended preventative care services. This set of studies included 18 good-quality, 157 fair-quality, and 7 poor-quality studies. • A meta-analysis of 22 studies (55.0%) which provided sufficient data to calculate a common endpoint indicated that CDSSs increase preventative care service ordered/completed with an odds ratio of 1.37 (95% confidence interval 1.16 to 1.62). • CDSSs that demonstrated an impact on the appropriate ordering preventative care procedures were conducted in both the academic and community ambulatory setting, were locally developed, automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care and did not require a mandatory clinician response.
b. Recommended clinical study ordered/completed	Moderate	<ul style="list-style-type: none"> • 24 of our included studies (18.3%) examined the impact of CDSSs/KMSs on the ordering and completion of recommended clinical studies. This set of studies included 14 good-quality, 6 fair-quality, and 4 poor-quality studies. • A meta-analysis of 17 studies (70.8%) which provided sufficient data to calculate a common endpoint indicated that CDSSs increase appropriate clinical studies ordered/completed with an odds ratio of 2.04 (95% confidence interval 1.49 to 2.81). • Although there was strong evidence from studies conducted in the academic and community ambulatory settings that CDSSs integrated in CPOE or EHR systems, locally developed CDSSs that provided recommendations to providers synchronously at the point of care and did not require a mandatory clinician response are effective at improving appropriate ordering of clinical studies; 2 of the 3 key papers reported a negative impact of CDSSs on the ordering of clinical studies and therefore, our confidence in the impact is lessened.
c. Recommended treatment ordered/prescribed	High	<ul style="list-style-type: none"> • 61 of our included studies (46.6%) examined the impact of CDSSs/KMSs on the ordering or prescribing of therapy. This set of studies included 36 good-quality, 17

Key Question	Level of Evidence	Conclusions
		<p>fair-quality, and 8 poor-quality studies.</p> <ul style="list-style-type: none"> A meta-analysis of the 39 studies (63.9%) which provided sufficient data to calculate a common endpoint indicated that CDSSs increase treatment ordered/prescribed with an odds ratio of 1.55 (95% confidence interval 1.28 to 1.89). CDSSs that improved treatment ordering/prescribing were implemented in academic and community ambulatory settings, were system-integrated, locally developed, provided recommendations to providers synchronously at the point of care and did not require a mandatory clinician response.
d. Impact on user knowledge	Insufficient	<ul style="list-style-type: none"> 5 of our included studies (3.8%) examined the impact of CDSSs/KMSs on user knowledge. This set of studies included 0 good-quality, 4 fair-quality, and 1 poor-quality studies
<i>Clinical outcomes:</i>		
a. Morbidity	Moderate	<ul style="list-style-type: none"> 25 of our included studies (19.1%) examined the impact of CDSSs/KMSs on morbidity. This set of studies included 14 good-quality, 9 fair-quality, and 2 poor-quality studies. A meta-analysis of 15 studies (60%) that provided sufficient data to calculate a common endpoint indicated a combined relative risk of 0.934 (95% CI 0.867 to 1.006). There is modest evidence from the academic setting that CDSSs that provided recommendations to providers synchronously at the point of care are effective or demonstrated a trend toward a reduction in patient morbidity.
b. Mortality	Low	<ul style="list-style-type: none"> 6 of our included studies (4.6%) examined the impact of CDSSs/KMSs on mortality. All studies in this set were rated as good quality. A meta-analysis of the 6 studies (100%) reported a combined relative risk of 0.9048 (95% CI 0.7564 to 1.082). Although all of the studies were high-quality, less than half of the studies were evaluated for at least a year or with more than 2000 patients.
c. Length of stay	Low	<ul style="list-style-type: none"> 5 of our included studies (3.8%) examined the impact of CDSSs/KMSs on length of stay. All studies in this set were rated as good quality.

Key Question	Level of Evidence	Conclusions
		<ul style="list-style-type: none"> • A meta-analysis of 4 studies (80%) which provided sufficient data to calculate a common endpoint indicated a combined relative risk of 0.977 (95% CI 0.884 to 1.081). • There is limited evidence from the academic setting that CDSSs that automatically delivered system-initiated recommendations synchronously at the point of care trends toward reducing length of stay.
d. Health-related quality of life	Low	<ul style="list-style-type: none"> • 5 of our included studies (3.8%) examined the impact of CDSSs/KMSs on health-related quality of life. This set of studies included 2 good-quality, 2 fair-quality, and 1 poor-quality studies. • The majority of these studies were evaluated for at least a year, and all included a sample size between 500 and 1000. • There is limited evidence from the ambulatory setting that system-integrated, locally developed CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrate a trend toward higher quality of life scores.
e. Adverse events	Low	<ul style="list-style-type: none"> • 6 of our included studies (4.6%) examined the impact of CDSSs/KMSs on health-related quality of life. This set of studies included 4 good-quality, 12 fair-quality, and 1 poor-quality studies. • A meta-analysis of the 6 studies (100%) reported a combined relative risk of 0.923 (95% CI 0.770 to 1.107). • Although the majority of the studies were high-quality, the majority of these studies were evaluated for less than a year and did not include a sample size larger than 2000 patients. • There is limited evidence from the academic setting that system-integrated CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrate an effect on reducing or preventing adverse events.
<i>Economic outcomes:</i>		
a. Cost	Low	<ul style="list-style-type: none"> • 20 of our included studies (15.3%) examined the impact of CDSSs/KMSs on cost. This set of studies included 9 good-quality, 6 fair-quality, and 5 poor-quality studies.

Key Question	Level of Evidence	Conclusions
		<ul style="list-style-type: none"> • The majority of these studies were evaluated for less than 1 year and included less than 2000 patients. • CDSSs from the inpatient and ambulatory settings that were locally developed and that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care demonstrated a trend toward lower treatment costs and total costs and greater cost-savings than the control groups and other non-CDSS intervention groups.
b. Cost-effectiveness	Insufficient	<ul style="list-style-type: none"> • 6 of our included studies (4.6%) examined the impact of CDSSs/KMSs on cost effectiveness. This set of studies included 1 good-quality, 5 fair-quality, and 0 poor-quality studies. • There is conflicting evidence from the ambulatory setting regarding the cost effectiveness of CDSSs that automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care. Some studies demonstrated a trend toward cost-effectiveness, however one of the included key papers reported a negative impact of CDSSs on cost-effectiveness and therefore, our confidence in the impact is additionally lessened.
<i>Use and implementation outcomes:</i>		
a. HCP acceptance	Low	<ul style="list-style-type: none"> • 22 of our included studies (16.8%) examined the impact of CDSSs/KMSs on HCP acceptance. This set of studies included 9 good-quality, 10 fair-quality, and 3 poor-quality studies. • Studies suggested that high levels of acceptance (acceptance rate greater than 75%) of recommendations from CDSSs that automatically delivered system-initiated (push) recommendations to providers are the exception rather than the rule.
b. HCP satisfaction	Moderate	<ul style="list-style-type: none"> • 18 of our included studies (13.7%) examined the impact of CDSSs/KMSs on HCP satisfaction. This set of studies included 9 good-quality, 6 fair-quality, and 3 poor-quality studies. • The majority of these studies were evaluated for at less a year and only 10% included a sample size larger than 2,000 patients. • CDSSs that were well-received by providers were implemented within the academic and community ambulatory settings, were system-integrated, locally

Key Question	Level of Evidence	Conclusions
		developed, automatically delivered system-initiated (push) recommendations to providers synchronously at the point of care and did not require a mandatory clinician response.
c. HCP use	Low	<ul style="list-style-type: none"> 15 of our included studies (11.5%) examined the impact of CDSSs/KMSs on HCP use. This set of studies included 5 good-quality, 8 fair-quality, and 2 poor-quality studies. Only 2 of the included studies documented usage over 80%. Among studies evaluating clinical or economic outcomes, none of these studies demonstrated provider use of CDSSs greater than 80%.
d. Implementation	Insufficient	<ul style="list-style-type: none"> 3 of our included studies (2.3%) examined the impact of CDSSs/KMSs on HCP use. This set of studies included 0 good-quality, 1 fair-quality, and 2 poor-quality studies There is insufficient evidence of how CDSSs/KMSs impacted implementation in practice and no high-quality studies specifically examined this outcome.
<i>Relationship-centered outcomes:</i>		
Patient satisfaction	Insufficient	<ul style="list-style-type: none"> 7 of our included studies (5.3%) examined the impact of CDSSs/KMSs on patient satisfaction. This set of studies included 4 good-quality, 2 fair-quality, and 1 poor-quality studies. Although the majority of the studies were high-quality, there is conflicting evidence that CDSSs had a positive effect on patient satisfaction. While some studies did not find that provider use of CDSSs increased satisfaction with the care received or overall visit, there was evidence from studies with evaluation periods of at least 2 years that the intervention patients were more satisfied than those in the control group.
Key Question 4: What generalizable knowledge can be integrated into electronic knowledge management and CDSSs to improve health care quality?		
(a) Knowledge from published evidence about electronic knowledge management and CDSSs to improve health care quality based on different types of measures (health care process, relationship-centered, clinical, economic)	Moderate	<ul style="list-style-type: none"> The most common source of knowledge incorporated into CDSSs was derived from structured care protocols (60 studies, 45.8%) and clinical practice guidelines (33 studies, 25.2%) that focused on a single or limited set of medical conditions.

Key Question	Level of Evidence	Conclusions
(b) How a clinician's expertise/proficiency/informatics competency using the electronic knowledge management and CDSS affects patient outcomes (one type of measure)	Insufficient	<ul style="list-style-type: none"> • Clinician expertise was not reported in 46 of the included studies (35.1%). In 35 studies (26.7%), CDSS recommendations were delivered using a paper-based format and so clinician expertise in using the CDSS was not relevant. • 50 studies (38.2%) reported data on clinician expertise in using CDSSs although the definition and reporting of this expertise was variable and the relationship between this expertise and patient outcomes was sparse.

Future Research

In the previous chapter, we identified several areas in which rigorous evidence related to CDSSs /KMSs was lacking. In this chapter we propose activities through which these identified gaps could be filled by future research studies that investigate issues related to CDSS content, recipients, outcomes, and implementation. First, in the area of CDSS content, CDSSs need to mature to the next generation in which the breadth of comorbid conditions for a given patient are routinely addressed. Such studies will need to explore how advice about multiple care issues and disparate CDSSs can be reconciled and how recommendations should be prioritized to avoid alert fatigue. Along these lines, studies are also needed to determine how CDSS content can be delivered most effectively for each clinical decision support niche. Such studies can determine if interruptive (pop-up alerts and reminders) or noninterruptive (order sets, smart forms, dashboards) are preferable as well as how the users should interact with the content from a specific type of CDSS: push versus pull, mandatory versus voluntary versus no user response, explanation versus no explanation for noncompliance, and so on. Second, studies evaluating the impact of KMSs are needed across the board. The KMS field is in its infancy, and such studies need to demonstrate when and how knowledge retrieval systems and point-of-care knowledge references are effective and useful.

Future studies will also need to explore who the optimal recipients of clinical decision support advice should be. With the growth of team-based care delivery models, studies are needed to ascertain who on the team other than physicians should receive which type of advice and how the delivery of advice can be orchestrated to facilitate team-based care coordination.

More studies are needed to demonstrate how CDSSs impact hard clinical outcomes to make real differences in health and wellness and not just improve process measures. Additionally, the costs of CDSSs need to be investigated, and the economic attractiveness of clinical decision support needs to be determined. The case needs to be made for CDSS cost effectiveness and subsequent return on investment in order to promote and expand CDSS utilization. Future studies also need to explore the unintended consequences of clinical decision support, particularly as multiple comorbid conditions are included and recommendations are delivered to multiple members of a care delivery team. As outcomes are measured with disparate CDSSs in diverse environments, the need to standardize metrics for workload, efficiency, costs, process measures, and clinical outcomes across systems must be addressed. Research is needed to determine what metrics best assess the effectiveness of clinical decision support and how these metrics can be standardized.

With regard to promoting extensive use of clinical decision support, models for porting CDSSs across settings will need to be developed and evaluated. Studies will need to validate the concept of CDSS knowledge sharing across applications and institutions as proposed in recent position papers.^{171,172} Can centralized knowledge repositories be effective in meeting the clinical decision support needs for region or the nation as a whole? At the level of individual systems, it will be useful to identify which CDSS features genuinely make a difference in effectiveness and user satisfaction. From the analysis conducted through this report, we have identified a cluster of features that are associated with a favorable impact of a CDSS; however, the many features are interrelated, and the available studies do not allow us to isolate individual features or even feature groups. As CDSSs become more ubiquitous, studies can be performed that assess CDSSs with and without selected features in order to determine with greater clarity the relative

importance of individual features. In addition to the features of the CDSS itself, characteristics of the environment and workflow into which a CDSS is deployed, and characteristics of the intended CDSS users, needed to be identified and investigated so that the impact of these characteristics on the success of the CDSS can be determined. Once the system, environmental, workflow, and user characteristics are delineated with regard to their influence on CDSS effectiveness, the system, environment, workflow, and users can be proactively adapted to optimize CDSS integration.

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Abbreviations

ack	acknowledgement
AE	adverse event
AHRQ	Agency for Healthcare Research and Quality
async	asynchronous
AVM	automated voice message
C	control (group)
CAD	coronary artery disease
CAIP	computer-assisted insulin protocol
CDSS	clinical decision support system
CHF	congestive heart failure
CI	confidence interval
com	commercial
CPOE	computerized physician/provider order entry
DSM	Diagnostic and Statistical Manual of Mental Disorders
DVT	deep vein thrombosis
ED	emergency department
EHR	electronic health record
EMR	electronic medical record
ER	emergency room
FOBT	fecal occult blood test
FRM	Framingham risk score
GP	general practitioner
HCP	health care provider
HIT	health information technology
HMO	health maintenance organization
HRQOL	health-related quality of life
I	intervention (group)
ICC	intraclass correlation coefficient
ICU	intensive care unit
IQR	interquartile range
KMS	knowledge management system
KUB	abdominal radiographs (kidney, ureter, bladder)
LDL	low density lipoprotein
mg/dl	milligrams per deciliter
MI	myocardial infarction
ml	milliliter or milliliters
mo	month or months
N or n	number
NA	not applicable
NPT	near-patient testing
NR	not reported
ns or NS	not significant
OR	odds ratio

p	probability
PA	physician assistant
PCP	primary care physician
PDA	personal digital assistant
PE	pulmonary embolism
PICOTS	population, intervention, comparator, outcome, timing, setting
PTSD	posttraumatic stress disorder
QALY	quality-adjusted life year
RC	relative change
RCT	randomized controlled trial
RR	risk ratio
Sbp	systolic blood pressure
SD	standard deviation
SE	standard error
sync	synchronous
UC	usual care
UKPDS	United Kingdom Prospective Diabetes Study
VA	Veterans Administration
vs	versus
wk	week or weeks
yr	year or years