Laboratory test ordering in inpatient hospitals: a systematic review on the effects and features of clinical decision support systems

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Abstract

Background: Studies have revealed inappropriate laboratory testing as a source of waste. This review aimed at evaluating the effects and features of CDSSs on physicians' appropriate laboratory test ordering in inpatient hospitals.

Method: Medline through PubMed, SCOPUS, Web of Science, and Cochrane were queried without any time period restriction. Studies using CDSSs as an intervention to improve laboratory test ordering as the primary aim were included. The study populations in the included studies were laboratory tests, physicians ordering laboratory tests, or the patients for whom laboratory tests were ordered. The included papers were evaluated for their outcomes related to the effect of CDSSs which were categorized based on the outcomes related to tests, physician, and patients. The primary outcome measures were the number and cost of the ordered laboratory tests. The instrument from The National Heart Lung and Blood Institute (NIH) was used to assess the quality of the included studies. Moreover, we applied a checklist for assessing the quality and features of the CDSSs presented in the included studies. A narrative synthesis was used to describe and compare the designs and the results of included studies.

Result: Sixteen studies met the inclusion criteria. Most studies were conducted based on a quasi-experimental design. The results showed improvement in laboratory test-related outcomes (e.g. proportion and cost of tests) and also physician-related outcomes (e.g. guideline adherence and orders cancellation). Patient-related outcomes (e.g. length of stay and mortality rate) were not well investigated in the included studies. In addition, the evidence about applying CDSS as a decision aid for interpreting laboratory results was rare.

Conclusion: CDSSs increase appropriate test ordering in hospitals through eliminating redundant test orders and enhancing evidence-based practice. Appropriate testing and cost saving were both affected by the CDSSs. However, the evidence is limited about the effects of laboratory test CDSSs on patient-related outcomes.

Background

The results of laboratory tests have an important impact on patients' care, as they influence physicians' decisions including admission, drug orders, and discharge as well as monitoring and managing the vast majority of diseases. However, studies indicate that diagnostic tests are being used inappropriately as a meta-analysis result showed that almost 20% of laboratory tests are over-utilized and 45% are under-utilized [1]. A study has indicated that only 1-5% of chemistry tests and 1-3% of hematology tests have led to an action; action in this study meant any alternation from what would have been done without the test result [2]. Moreover, about 70% of residents, in one study were reported that they were ordering unnecessary daily laboratory tests [3].

Inappropriate test ordering can increase the risk of false positive results as well as medical errors [4]. Overutilization can potentially cause patient discomfort including phlebotomy-induced anemia [5]. Underutilization can also result in delayed or missed diagnosis. Studies have found that a vast majority of claims both in outpatients and emergency department belongs to missed diagnosis resulting in death or serious harm to patients [6, 7]. Overcrowded diagnostic services, increased length of stay (LOS), and waste of valuable healthcare resources are amongst other consequences of inappropriate testing [8-10]. Conversely, it imposes a lot of costs to healthcare as 3% of health care expenditures in the USA belong to laboratory testing [11-13].

Information technology [IT] has provided some solutions to decrease inappropriate laboratory tests ordering. Some of these technologies are electronic medical record (EMR) [14], electronic health record (EHR) [15], computerized physician order entry (CPOE) [16], and clinical decision support systems (CDSS) [17]. Of all these, CDSS has more potential to support physicians when deciding about ordering a test or interpreting the results. However, studies have shown inconsistent results about the impact of CDSSs on physicians' performance and patients outcomes [18, 19]. Thus, there is a need for a scoping review on the effects of CDSSs on ordering appropriate laboratory tests.

Studies evaluating the impact of CDSSs on diagnostic testing showed no improvement in clinical outcome but small positive improvement on physicians behavior regarding diagnostic test ordering [20, 21]. There are two similar systematic reviews focusing on laboratory test ordering specifically. The first is Maillet et al. (2018) study [22] which addressed the IT impact on laboratory tests ordering process in primary healthcare. This study did not focus on the effectiveness of CDSSs rather it focused on some specific IT interventions. It also included the studies conducted in primary healthcare. The second systematic review by Delvaux et al. (2017) [23] included the studies conducted in diverse healthcare settings (i.e. primary healthcare, hospital outpatient, and hospital inpatient). They found that CDSSs had little or no effect on clinical outcomes but some effects on physician compliance rate. Neither of the studies has investigated the features of the included CDSSs mentioned as a suggestion in Delvaux et al. study [23]. Taking into account all studies conducted in inpatient hospitals and aimed at improving laboratory testing process, without considering study designs, might produce different results. Furthermore, features of successful CDSSs need to be investigated. Thus, the goal of current study was to conduct a systematic review on the effects and features of CDSSs on physicians' appropriate laboratory tests ordering in inpatient hospitals.

Methods

Research Question

Do CCDSSs improve practitioners' appropriate laboratory test ordering in hospitals?

Search Strategy and Study Selection

A search strategy was developed using keywords, MeSH terms, and major subject headings to identify published papers in the literature and adaptations were made for each database. Four databases were queried: Medline (through PubMed), SCOPUS, Web of Science, and Cochrane. We considered studies published

till 21 January 2020 without any time limitation. The search strategy consisted of a combination of keywords and Mesh terms related to clinical laboratory services (laboratory test utilization), CDSSs, and hospitals. The search strategy is presented as supplementary (supplementary A).

After removing duplicates, two authors (SZ and MS), working independently, selected the papers based on eligibility criteria. Titles and abstracts were screened for inclusion. The full text of potentially relevant papers was obtained, and both inclusion and exclusion criteria were considered. The reference lists of the identified papers were also searched to include any other paper missed during the electronic searches. Authors resolved disagreements through discussion and consensus, and any remaining disagreements were resolved by another author (EN).

Study Selection Criteria

Inclusion Criteria

Type of Studies

A variety of evaluation study designs were included: randomized controlled trials (RCTs), non-randomized controlled clinical trials (CCTs), prospective observational studies, before-after, and interrupted time series (ITS).

Type of Population

The study populations in the included studies were laboratory tests, physicians ordering laboratory tests, or the patients for whom laboratory tests were ordered.

Types of Interventions

Studies using CDSSs as an intervention to improve laboratory test ordering as the primary aim were included. In current study, a CDSS is considered as a health information technology system designed to provide assistance to physicians at the time of decision-making. CDSSs can facilitate access to data which are required to make decisions, provide reminders while a patient encounters, assists in both recognizing a diagnosis and entering appropriate orders, and alerts healthcare providers when new patterns in patient data are observed [22,24]. In studies with multifaceted interventions, the effects of CDSS intervention were considered independently and the cases where separating the CDSS impact was impossible were excluded.

Type of Outcomes

The included papers were evaluated for their outcomes related to the effect of CDSSs, which were categorized based on test-related, physician-related, and patient-related outcomes. These outcomes include: diagnostic yield and diagnostic detection rate, the number and cost of laboratory test ordered, laboratory turnaround time (TAT), STAT tests, guideline adherence for laboratory test ordering, physicians knowledge and attitude toward laboratory testing, patients outcome (e.g. patients safety, readmissions, death, length of stay and disposition). Test-related outcomes were the proportion of tests, cost of tests, test intervals, number of STAT request, and laboratory TATs. Physician-related outcomes include diagnostic yield and diagnostic detection rate, adherence or order cancellation after the reminders (or overriding the reminders), and physicians knowledge and attitude. Patient-related outcomes were patients' complications, patients' disposition, length of stay (LOS), and mortality rate.

Exclusion Criteria

Exclusion criteria were studies published in any languages rather than English, conducted in outpatient or primary care settings, used as interventions rather than CDSS, conducted in an unreal clinical environment or based on a scenario (in a simulated setting i.e. to test a system). Moreover, all retrospective studies were excluded.

Quality Assessment

The National Heart Lung and Blood Institute (NIH) quality assessment tools for each type of studies [25] were used to assess the methodological quality of the included studies. The variety of study designs necessitated the use of different NIH quality assessment tools, That is Quality Assessment of Controlled Intervention Studies, case-control studies, and before-after studies with no control group. NIH tool categorizes studies as good, fair, or poor. Included studies were independently assessed by two reviewers (SZ & MS) and any disagreement over scoring was resolved by consensus.

Quality and features of the CDSSs were assessed using a checklist derived from Goldzweig et al study [26]. This checklist considers the design and the degree of reporting information about CDSS and implementation characteristics. The checklist consists of three domains: CDSS design, data entry source, and implementation source.

Data Extraction

A form was designed to extract data from each of the included studies. For each study the following data were extracted: study design, sample size, intervention description, and results. One author (SZ) extracted data which were subsequently reviewed and confirmed by another reviewer (EN).

Data Analysis

A narrative synthesis was used to describe and compare the designs and the results of included studies. We categorized studies based on different features of CDSSs, outcome category, and effects of CDSSs. The effect of interventions were reported based on statistically significant positive, positive without

statistical argument, no effect (not statistically significant), negative without statistical argument, or statistically significant negative [27]. Meta-analysis was not performed due to the variety of outcomes and results.

Results

Study Selection (Figure 1)

The literature search identified 2784 records, as well as two additional papers [28, 29] identified through other sources (snowball-search), 739 of which were duplicates. The papers were screened for eligibility by title and abstract, resulting in 74 potential papers for the full-text review. During the full-text reviewing, 58 papers were excluded. Finally, 16 studies were deemed eligible for inclusion.

Characteristics of the Included Studies

A substantial number of the included studies were performed during the recent decade. Overall, 81.2% of the included studies were published after 2010 and, of these, 69.2% were published after 2015. Most of the included studies were conducted in the United States (n=12, 75%); and one was conducted in each of the following countries: Canada [30], United Kingdom [31], Italy [32], and France [33].

Table 1) Characteristics of the Included Studies

Quality Assessment (table 2)

One study was RCT [28], one case-control [39], and the others (n=14) were quasi experimental studies (appendix B). Most of the included studies (n=11, 68.7%) were of intermediate quality, the remaining were of good quality. The main limitations of the included studies were not being blinded (93.7% had not blinded assessors) and lack of a clear specified description of inclusion and exclusion criteria (43.7%). The results are presented as a supplementary (supplementary B).

The quality assessments of the CDSSs are presented in table 2. Almost all CDSSs were integrated with CPOEs (93.7%), providing real-time feedback (93.7%) without any recommended action (100%). Most CDSS classifications of the studies (43.7%) are in C category which required the ordering clinician to justify why they were overriding the provided decision support recommendation (see table 2 legend). Four studies (25%) were integrated with and automated through EHR. Eight studies (50%) reported that they had tested CDS before implementation. Only two studies (12.5%) reported user training about the intervention; in other cases users were mostly trained about the indications required for ordering a specific test or similar things. Other characteristics, barriers, and facilitators affecting implementation of CDSS were: the role of order sets, "adjustment" period, stakeholder and champion leaders engagement, appropriate environment, ease of repeating targeted tests, testing options constrains, paradoxical prompting generated by CDSS, and daily orders which would not trigger the audits.

CDSS interventions were mostly in the form of a reminder about duplicate tests in a specific timeframe, rule-bases providing knowledge about when it is appropriate to order the specified test, or predefined appropriateness criteria physicians had to determine before ordering the tests. These interventions support physicians' informed decision-making in the first step of testing process when they are deciding about ordering a test.

Table 2: Quality Assessment of the CDSSs

Effects of CDSSs on Outcomes (Table 3)

The included studies had mostly investigated laboratory test-related outcomes. Generally, CDSS interventions showed positive effects on all outcomes.

Laboratory Test-related Outcomes

All the included studies have investigated the effects of CDSSs on proportion of laboratory tests. In general, studies showed positive impact on proportion of laboratory tests. The reported proportion of reduction varied from 21% [38] to 55% [37] among the studies. The study by Boon-Falleur et al. [31], assessed as fair quality, applied a rule-based expert system for classified patients (Pre-transplant assessment, post-transplant assessment, and transplant monitoring) in liver transplant unit. The rule-based system increased laboratory utilization in pre-transplant assessment patients. The authors believed that, after the introduction of the system, physicians were asked to answer some precise questions, at patient admission, and it caused more often ordering of specialized diagnostic tests. However, it caused an overall reduction in laboratory resources consumption for transplanted patients. Eaton et al. [36] performed a multifaceted intervention in their good quality study indicating no effect on the rate of folate tests orders, but 43% reduction in the rate of hepatitis C virus tests. The study by Rudolf et al. [43] demonstrated that although recurrent daily laboratory tests reduced, the total tests volume remained unchanged. They stated that daily tests account for a small number of total tests; moreover, physicians may not decrease overall testing but instead shift testing to patients or conditions where it was more needed [43]. Rosenbloom et al. [42] used three CDSS interventions, two of which had a positive impact and one of which had a negative impact on magnesium ordering.

Cost of tests is also reported in half of the included studies. Results revealed that CDSSs had positive impact on reducing cost of tests. In most studies, except the one by Bridges et al. [34], with good quality, the reduction in the cost of laboratory tests was not analyzed with a statistical method [28, 30, 32, 37, 38, 41]. Test interval was only investigated in Bates et al., a good quality study [28], which showed a positive impact. "STAT" request of laboratory tests has only been investigated in a study by Boon-Falleur et al. [31] showing a positive impact.

(Table 3) Effects of CDSS interventions on laboratory testing outcomes

Physician-related Outcomes

Three studies reported the outcomes related to guideline adherence and all indicated positive impacts of CDSS. Compliance rate was measured based on the proportion of cancelled orders after the provision of the reminders or recommendations by CDSS. Boon-Falleur et al. [31] showed that 78% of the total performed laboratory tests were proposed by the static assessment protocols. However, overall compliance to the dynamic protocols was 45%. Actually the compliance to the static rules was more in comparison with the dynamic rules. Bates et al. [28] showed that 69% of the proportion of laboratory orders was canceled after the provision of alert. They also found that only 27% of ordered redundant tests were performed. In the study by Nies et al. [33] the compliance rate to the displayed alerts was 24%. No outcome is reported regarding diagnostic detection rate and physicians' knowledge.

Patient-related Outcomes

Patient-related outcomes were addressed in five studies. Cancellation of redundant tests based on the displayed alerts in some studies [28, 39, 41] resulted in little or no loss of clinical information as well as no complication. Bridges et al. [34] showed that patients with duplicate tests had higher mortality rate than those without duplicate tests. They also had a worse disposition after discharge, indicating that those with redundant tests were generally sicker. Redundant tests are those which are performed before a defined time frame (interval) for repeating that test [28, 34, 41]. Duplicate tests are also defined as a test that is ordered after a previous test of the same type that is unlikely to change clinical plan [34]. In this study, the patients LOS also remained unchanged after the intervention.

Discussion

Generally, the studies were mostly of moderate methodological quality with only one RCT out of the 16 included studies as well as most studies being conducted after 2015. The majority of included studies were addressing the effect of CDSSs on laboratory test-related outcomes. The results showed improvement in laboratory test-related and physician-related outcomes. Patient-related outcomes were not well investigated in the included studies.

Most studies conducted after 2015 suggested a new research agenda in health information technology. It also indicates that attentions to resource utilization for appropriate usage of laboratory tests have been increased recently. It might also be attributed to limited resources as well as increased cost of healthcare. Healthcare resource utilization and the costs by different diseases show a high economic burden highlighting need for taking some actions to decrease costs [45-47]. The results of this review showed that CDSSs have the ability to improve laboratory test utilization in some cases including hepatitis B virus, Clostridium Difficile, magnesium, B-Type natriuric peptide, TFT, ESR, and heparin-induced thrombocytopenia tests.

Laboratory Test-related Outcomes

Appropriate testing and cost saving were both affected by the CDSSs which is consistent with a similar systematic review on outpatient setting [22]. It is also consistent with a narrative review by Bindraban et al. [48] showing nearly all interventions in educational, CPOE, and audit and feedback category caused reduction in test order volume. Thesystematic review by Roshanov et al. [20] also indicated that those systems aiming at reducing test ordering rate had positive impact. However, the results are inconsistent with Delvaux and colleague systematic review. They found that CDSSs designed to change laboratory testing behavior for diabetes, HIV, and anticoagulation had little or no influence on clinical outcome. Our study included studies aiming at improving laboratory testing process as the primary aim. However, most studies included by Delvaux et al., as mentioned in introduction section, had different objective, for instance computer-aided dosing, and further evaluated its impact on diagnostic testing. Thus, it seems CDSSs specifically designed to affect laboratory tests are more influential. Eaton et al. [36] showed that CDSSs might be effective for some tests and ineffective for some others. There was only one study [42] that found a negative impact in magnesium ordering attributed to CDSS. The CDSS was supposed to regulate magnesium ordering; they developed a CDSS in a way that three tests (i.e. magnesium, calcium, and phosphorus) could be ordered from one user interface of CPOE. This may have caused an unintentional prompt to order these tests together without original plan. Cost reduction in laboratory tests was reported in several studies [28, 30, 32, 34, 37, 38, 41]. But it is important to mention that the quality of the studies was fair and the results were not analyzed statistically. Thus, the conclusion about cost reduction sounds difficult. However, it is stated that the reported cost reduction is an underestimation of true cost savings since they only assessed consumables costs; the associated resources (i.e. equipment, personnel, test tubes, etc.) should be included in the calculation.

Physician-related Outcomes

The studies reporting physician-related outcomes [28, 31, 33] showed positive effect on compliance to the CDSS recommendations. A systematic review by Delvaux et al. [23] also demonstrated a positive impact in compliance with recommendations made by CDSSs. Roshanov et al. [20] also concluded that CDSSs had positive impact on physicians' diagnostic test ordering behaviors. However, they believed that the contributing factors resulting in success or failure are unclear. Main et al. found that if they consider the result of both primary and secondary outcome then CDSSs is effective on physicians' behaviors.

Patient-related Outcomes

The results also indicated that the evidence pertaining to the effects of CDSSs on patient-related outcomes is limited. Overall, CDSSs may make little or no difference to patient outcomes including patient complications, patient disposition, or mortality rate [28, 34, 39, 41]. For instance, in the study by Bates et al. [28], three of the eight urinalysis cancelled tests displayed a few red blood cells, while previous specimen had been negative. It is inferred from these findings that cancelling the orders due to a CDSS suggestion, probably lead to no adverse event to patients. The study by Bridges et al. [34] showed that patients with duplicate tests had higher mortality rate than those without duplicate tests; they also had a worse disposition after discharge, indicating those with redundant tests were generally sicker. Thus, less mortality rate cannot be only attributed to CDSS effect and needs more investigation. Patient experience like decreased phlebotomy and other possible improved outcomes like decreased risk for false-positive test results should be investigated in future studies.

Strengths and Limitations

A comprehensive search strategy, without any time period restriction, was performed to find the maximum number of relevant studies. To avoid missing any important findings, a variety of interventional study designs were included. We assessed the effects of CDSSs not only on proportion of test orders and associated costs but also on physician-related and patient-related clinical outcomes.

A limitation of this review is that due to exclusion of non-English language papers and conference proceedings, some relevant studies might have been missed. Another limitation is the exclusive focus on studies on reducing unnecessary testing as the main outcome. Most studies conducted in this field were performed using a quasi-experimental design making the conclusion about the impacts difficult due to possible biases.

Implication

Applying a clinical algorithm and hard stop alerts for preventing specified tests would result in more reduction in tests volume. CDSSs should be evaluated for specific laboratory tests to make sure only effective alerts would be displayed [36]. Nonetheless, allowing overrides may be effective for clinicians' acceptance of the system. Nonintrusive alerts should be evaluated to make sure only effective alerts continue to be displayed so as to prevent rising alert fatigue [36]. Alert fatigue causes both important and non-important alerts to be overridden by clinicians. Thus, considering a balance between system flexibility and hard-stop alerts is important in designing a CDSS. It is suggested that the intervention must be sustainable through providing awareness to the changes, which will bring about better compliance. Impact on physician-related outcomes can be promoted over time, since physicians possibly experience an "adjustment" period at the beginning of the intervention; therefore, they need time to become familiar with the intervention [34]. Although physicians' attitude and requirements are important factors contributing in more acceptances and perceived usefulness of CDSS, less attention has been paid to them. It has been shown that simple static rules had higher compliance rates than complicated dynamic rules [31]. CDSSs design should not allow two or more tests to be ordered from a single interface, because it may contribute in unintentional prompt to order those tests together and increase tests ordering.

Future Research Directions

Since most studies were conducted after 2015, indicating a new research agenda, there is a need for more studies investigating effective information technology-based approaches to manage health resources utilization. Moreover, considering the majority of the studies were performed using a quasi-experimental design, there is an essential need for further studies with more robust study designs. Also, to make sure about the effects of CDSSs on test interval, STAT tests, and TAT, further studies are needed. Considering lack of evidence on potential negative effects resulting from the cancellation of the tests based on CDSS recommendations, future research should evaluate these effects, especially potential harm to patients. Although some physicians need guidance when interpreting some tests [49, 50] and CDSSs have the potential to aid them, according to our review there was no physician aid for interpreting the result; new research can investigate the effects of CDSSs as a physician aid for interpreting the laboratory tests results.

Conclusion

Current systematic review indicate that CDSSs increase appropriate test ordering through eliminating redundant test orders and enhancing evidence-based practice in hospitals. The literatures showed that CDSSs have the potential to influence on cost savings. However, evidence is limited about the impact of cancelling order tests on patient health and needs further studies. As suggested, there is an essential need for further studies with more robust study designs like randomized controlled trials.

List Of Abbreviations

CDSS: Clinical Decision Support System

EMR: Electronic Medical Record

EHR: Electronic Health Record

CPOE: Computerized Physician Order Entry

TAT: Turnaround Time

RCT: Randomized Controlled Trials

CCT: Controlled Clinical Trials

ITS: Interrupted Time Series

ED: Emergency Department

IG: Intervention Group

CG: Control Group

TFT: Thyroid Function Test

TSH: Thyroid Stimulation Hormone

C. difficile: Clostridium difficile

Declarations

Ethics Approval and Consent to Participate

The study is approved by the ethics review board of the Vice-chancellor for Research Affairs of KaUMS (IR.KAUMS.NUHEPM.REC.1398.005). **Consent to participate is not applicable.**

Consent for Publication

Not applicable.

Availability of Data and Material

All data are available in the submission.

Competing Interest

The authors declare that there are no conflicts of interest.

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Authors' Contribution

EN and ZM supervised the study. SZ MS contributed in reading the articles for relevance and disagreements were solved by EN. SZ extracted the information of the included studies. SZ and EN have drafted the manuscript. All the authors have read and approved the manuscript.

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Tables

Table 1: Characteristics of the included studies

, tion,	Study design	Study duration	Setting	Population	Sample size	Intervention description	Main finding regarding the proportion of laboratory tests	Conclusion
al., A	RCT	4 months	A tertiary care hospital	Inpatients at the hospital	CG: 5886 patients IG:5700 patients	CPOE reminder: In the intervention group, if a test had previously been ordered within its test-specific interval, the physician received a reminder that the test had been performed recently or was pending; the result was showed if available. For the control group, duplication was determined in exactly the same way, but there was no reminder.	1) in the IG 69% cancelled the order after the reminder 2)In the CG, 51% of ordered redundant tests were performed, whereas in the IG only 27% of ordered redundant tests were performed (P<0.001). 3) During the preceding period, 20.5% of target tests were performed earlier than specific intervals, whereas during the study period, this rate was significantly lower in the IG (18.5%, P = 0.004) but not in the control group (19.6%, P = 0.19) 4) In the 4-month period preceding the intervention, there were 4.84 target tests per admission, compared with 4.24 during the study period in the intervention group and 4.28 in the control group (both P<0.0001)	Delivering about orde apparently laboratory effective. H many tests conducted correspond orders and were not so duplication was limited
et ited	Before-after	6 months	A pediatric liver disease unit	Patients with liver transplant	Before: 42 patients After: 175 patients	A rule-based expert system allows static and dynamic requesting rules to be defined for different clinical classifications of patients. The static rules allow the definition of "baseline" proposals within a precise time schedule. Dynamic rules allow the system to react to results of previously ordered tests. The attending physician may accept or amend the system's proposals by adding or removing requests to the proposed schedule.	1) An increase of the total number of tests requested per patient was observed 2) An overall reduction in laboratory resources consumption for transplanted patients (27%) 3) A decrease in the percentage of "STAT" requested tests (-44%). 4) The percentage of tests ordered in agreement with the protocols for those patients increased from 33% before the introduction of the expert system to 45% when the system was used.	The clinicia perspective system wou the total be clinical res improve th of laborato save time f laboratory
et A	Before-after	6 months	A tertiary care hospital	Patient admitted to the department of medicine	Before: 674 patients After: 692 patients	The intervention consisted of displaying a computerized alert informing that the clinician is ordering a recently ordered test.	1) In the pre-intervention period, 53 (7.9%) were duplicated and post-intervention 18 (2.6%) were duplicated (p < .001). 2) The alert significantly reduce associated costs of duplicated acute hepatitis profile tests (p ≤ .001).	Computeriz be effective redundant tests and e efficiency c system.
al., A	Before-after	6 months	A teaching hospital	All TSH, T3, and T4 ordered in Department of Medicine	Before: 2611 tests After: 2454 tests	A clinical algorithm for CDS and Hard Stops were incorporated into the EMR to decline ordering freeT3 or freeT4 without an abnormal TSH, also certain exceptions were predefined. In addition, if the TSH was abnormal a reflex	1) The fT3 to TSH ordering ratio similarly decreased by 55.2%, from 6.2% to 2.9% (P < 0.0001). 2) Post-intervention there was a decrease in the ratio of fT4 to TSH orders (fT4/TSH) of 35.2%, from 44.6% to 28.9% (P < 0.0001).	By a clinica support ab order TFTs observed a the numbe unnecessar ordered.

						rule was triggered and could automatically order freeT3 and freeT4.	3) TFT/TSH pre-intervention ratio was 52.2%, which decreased by 39.1%, to 31.8% post-intervention. (P < 0.0001).	
; al., A	Time-series	30 months	Hospital	Inpatient population admitted to general medicine service	Before: 14193 patients After: 13751 patients	Educational guide, nonintrusive ordering message, and noon conference. Appropriate indications for selected tests were incorporated into text accompanying the laboratory orders in hospital's HER. Physicians could ignore the text and proceed with the order.	1) The rate of folate tests ordered per monthly admissions showed no significant level change at the time of the intervention with only a slight decrease in rate of 0.0109 (P = .07). 2) There was a 43% decrease in the rate of hepatitis C virus tests per monthly admissions immediately AI with a decrease of 0.0135 tests per monthly admissions (P = .02).	Nonintrusi not have si effect on u laboratory
et	Time series	12 months	A tertiary care hospital	Erythrocyte Sedimentation Rate orders	Not mentioned	Educational content and CDSS: a series of appropriateness criteria for Erythrocyte Sedimentation Rate was incorporated into CDSS.	After CDS, ESR orders per week decreased from 386 to 151. When unlimited access was provided to select subspecialties, there was an increase in ESR orders per week to 241. This represents a decrease of almost 40% from baseline.	Their quali improveme could redu inappropri Sedimentat Rate testin computeriz
; al., A	Time series	12 months	A tertiary hospital, a 53-bed satellite facility	Specimens from children ≤12 months	485 specimens	Educational intervention, an evidence-based algorithm for appropriate clostridium difficile ordering, and CPOE requiring clinicians to mandatory complete 2 extra fields. nondiarrheal stool were automatically declined by laboratory, unless in cases with severe ileus or toxic megacolon.	After the intervention, the average percentage of specimens tested dropped to 53.8%.	Their CDSS resulted in drop in the specimens saved labo patient cos They obser sustained clinicians' practices in multiple ed efforts.
t 3, A	Time series	6 months	Three not-for-profit hospitals	Patients with B-Type Natriuric Peptide test	41306 patients	CPOE with embedded CDS: The CDS intervention is an expert rule that searches the system for a B-Type natriuric peptide lab value for the patient. An advisory alert was indicated to the ordering clinician if there was a value for the test and it was within the current hospital stay.	1) The CDS intervention reduced B-Type natriuric peptide orders by 21% relative to the mean.	Using CDS the potenti improving should be judiciously appropriate environmer
al.,	Before-after	6 months	A teaching hospital	A variety of tests requests including C reactive protein, TSH, ferritin, brain natriuretic peptide, etc	3539 test requests	CDSS: an electronic alert is automatically triggered by a potentially inappropriate test request. The alert contains a detailed explanation of the specific rule for appropriateness of the test.	The total number of test requests violating the preset criteria of inappropriateness constantly decreased over time (26% in the first three months of implementation versus 17% in the following period; p< 0.001).	A CDSS ale effective to the inappro laboratory generate si saving and physicians laboratory more effici
on et A	Before-after non-equivalent control group	26 months	A tertiary-care pediatric hospital	Children <36 months of age	Before: 141 patients After: 55 patients	An alert advising against ordering C. difficile tests in infants and young children based on the American	1) The average monthly testing rate significantly decreased for children 0–11 months old (P<.001) and 12–35	The averag testing rat difficile for months old without cor

						Academy of Pediatrics recommendations. Physicians could override it optionally.	months old (P< .001), but not for those children ≥36 months old (P= .3).	after the u: alert in tho positive for
al.,	Time series	36 months	A university teaching hospital	Patients with hepatitis B antigen test	Before: 2888 patients After: 1572 patients	CDSS: The alert is triggered when one of the targeted serological tests for hepatitis B virus is selected to be ordered. The Serology-CDSS stores a record of its execution each time a physician selects a viral serology test order. An alert is displayed if the most recent result of the targeted laboratory test for the patient is less than 90 days old.	1) In pre-intervention period 15.5% of viral serology tests were unnecessarily repeated. During the intervention period, 15.8% were repeated. Before the intervention, the mean proportion of unnecessarily repeated HBs antigen tests increased by 0.4% per month (p < 0.001). After the intervention, a significant trend change occurred, with a monthly difference estimated at -0.4% (p = 0.02) resulting in a stable proportion of unnecessarily repeated HBs antigen tests.	After CDSS implementa immediately was observ proportion unnecessar tests. CDSS also improv rate.
al., ne	Before-after	24 months	An academic hospital	Patients with C. difficile infection test	Before: 284 tests After: 268 tests	Clinicians were required to verify the determined criteria for appropriate ordering of C. difficile infection test. A warning email was sent to the physicians ordering the test without appropriate approval.	Baseline CDI testing rate declined from 284/10,000 to 268/10,000 patient-days post-intervention (p=0.02). The intervention decreased inappropriate testing by 64%.	The protoc appropriate well as dec hospital-on standardize ratio of C. infection.
et l, A	Time series	24 months	The Cleveland Clinic	more than 1000 tests of all patients	Not mentioned	CDSS: This tool informs the provider that the test being ordered is a duplicate. It also block unnecessary duplicate test orders during the computerized physician order entry	1) The proportions of reductions in the number of stool ova/parasite examinations was 54.1% (P<0.0001) 4) The proportions of reductions in the number of Giardia/Cryptosporidium enzyme immunoassay tests was 22.58% (P=0.2807) 3) The proportions of reductions in the number of stool culture tests was 49.1% (P<0.0001).	Real-time i: between th and the ph through CI decrease d orders. It s healthcare should also patient sat: well-being.
oom 005, A	Time series	5 years	An academic inpatient tertiary care facility	Clinicians at a university hospital	194,192 patients	The CDSS exhorted users to discontinue unnecessary tests recurring more than 72 hours into the future 2) Education regarding appropriate indications for testing. 3) CDS and CPOE systems targeted only magnesium ordering, displayed recent results, limited testing to one instance per order, summarized indications for testing, and required users to select an indication	At baseline, there were 539 magnesium tests ordered per week. This decreased to 380 (p = 0.001) per week after the first intervention, increased to 491 per week (p , 0.001) after the second, and decreased to 276 per week (p , 0.001) after the third.	A clinical d support int intended tc testing incr order rates unintended decision su
et 7, A	Time series	36 months	A tertiary care teaching hospital	Laboratory tests	61644 laboratory test ordes	Alert in the CPOE system: the alert appeared in the CPOE each time an order with frequency greater than one occurrence was selected. The justification for the order was also	1) 6,463 orders for recurrent daily laboratory tests were placed for a mean daily rate of 71.8 orders per day. 2) AI 44,900 orders for recurrent daily laboratory tests were	Our experie auditing ar feedback a crucial com changing o behavior. C orders alor a sufficient

| | | | | | | | captured by the CPOE, as providers were required to select one of three approved indications for the daily laboratory test or manually enter another indication. | placed for a mean daily rate of 44.8 orders per day, representing a highly significant decrease in daily laboratory test ordering 3) Total inpatient test volumes were not affected. | reduce in-la... costs |
| on 015, A | Before-after | 16 months | Two academic medical hospitals | Patients evaluated for heparin-induced thrombocytopenia | Before: 265 patients After: 146 patients | CDSS: A decision-support tool required providers to calculate the 4Ts (heparin-induced thrombocytopenia risk) score prior to ordering laboratory-based tests for anti-PF4/heparin antibody enzyme-linked immunosorbent assay testing | 1) We observed a significant decrease from 43 tests/month before to 22 tests/month (p<0.001) after the intervention. 2) We observed a trend toward decrease in the proportion of tested patients with low 4Ts scores (66% vs 56%, p = 0.069), | Our study ... that a clini... support too... within the ... ordering p... decrease u... testing for ... induced thrombocyt... |

CDSS: Clinical Decision Support System; CG: Control Group; CPOE: Computerized Physician Order Entry; ED: Emergency Department; IG: Intervention Group; RCT: Randomized control trial; TFT: Thyroid Function Test; TSH: Thyroid Stimulation Hormone.

Table 2
Quality assessment of the CDSSs

Author	CDSS design				Data entry source		Implementation characteristic				Are othe impl comp not disc
	Is it integrated with CPOE?	Does it give real time feedback at point of care?	Does the CDS suggest a recommended course of action?	CDSS Classification*	Is it automated through EHR?	Does clinical staff enter data specifically for intervention?	Was it pilot tested or used an iterative process of development/ implementation?	Was there any user training/clinician education?	Are the authors also the developers and part of the user group for the CDS?	Was there use of audit and-feedback (or other internal incentive)?	
Bates et al. (28)	Yes	Yes	No	C	Yes	No	NM**	NM	Yes	No	50% tests com were scre redu beca were as p orde
BoonFalleur et al. (31)	No	No	No	B	No	No	Yes	NM	NM	No	No
Bridges et al. (34)	Yes	Yes	No	B	NM	No	Yes	NM	No	No	Clin likel expe "adj peri they fami the
Dalal et al. (35)	Yes	Yes	No	D	Yes	No	Yes	Yes	Yes	No	No
Eaton at al. (36)	Yes	Yes	No	B	No	NM	No	NM	NM	No	No
Gottheil et al. (30)	Yes	Yes	No	C	NM	No	Yes	NM	Yes	Yes	the of st enga prio inte and deci lead depa char caus
Klatte at al. (37)	Yes	Yes	No	D	Yes	Yes	Yes	NM	NM	No	No

Levick at al. (38)	Yes	Yes	No	B	No	No	NM	NM	Yes	No	Use... shou... judi... in th... appr... envi...
Lippi at al. (32)	Yes	Yes	No	B	NM	No	NM	NM	Yes	Yes	No
Nicholson at al. (39)	Yes	Yes	No	C	NM	Yes	NM	NM	Yes	No	No
Niès at al. (33)	Yes	Yes	No	C	Yes	No	Yes	NM	Yes	No	Test... wer... cons... unb... seru... met... pan... sing... com... and... the... repe... targ...
Quan et al. (40)	Yes	Yes	No	D	NM	No	NM	NM	NM	Yes	No
Procop at al. (41)	Yes	Yes	No	D	NM	No	Yes	Yes	No	Yes	No
Rosenbloom at al. (42)	Yes	Yes	No	C	NM	Yes	NM	NM	Yes	Yes	Desi... CDS... inte... shou... into... the... pror... such... inte... migl... gene...

Rudolf at al. (43)	Yes	Yes	No	C	NM	Yes	NM	NM	NM	Yes	Prov use worl plac orde ente orde man wou trigg audi exan plac stag of o occu othe writ orde temp coul circu our proc acco daily for t anal
Samuelson et al. (44)	Yes	Yes	No	C	NM	Yes	NM	NM	NM	NM	No
Sum Yes	15	15	0	A: 0	4	5	8	2	8	6	
No	1	1	16	B: 5	3	10	1	0	2	9	
NM	0	0	0	C: 7	9	1	7	14	6	1	
				D: 4							

*Intervention Classification: "A" interventions provided information only; "B" interventions presented information on appropriateness or guidel specifically tailored to the individual patient, often as a pop-up or alert. Some of these interventions also recommended alternative intervention not include any barrier for the clinician to order the test; "C" interventions in general were similar to "B" interventions, but required the orderi clinician to justify with free text why they were overriding the decision support recommendation that a study was inappropriate (ie, a "soft stop interventions included a "hard stop," meaning the intervention prevented the clinician from ordering a test contrary to the CDS determination inappropriateness, until additional discussion with or permission obtained from another clinician or pathologist.

** Not Mentioned

Table 3

) Effects of CDSS interventions on laboratory testing outcomes

Outcome Category subcategory		Positive Statistically Significant Demonstrated		No effect	Negative Statistically Significant Demonstrated
Test-related	Proportion of tests	(28), (34), (35), (36), (32), (39), (33), (40), (42)*, (44)	(31), (36), (30), (37), (38), (41)	(31), (36), (43)	(42)*
	Cost of tests	(34)	(28), (30), (37), (38), (32), (41)		
	Test intervals	(28)			
	Number of STAT request		(31)		
Physician-related	Guideline adherence		(31), (33)		
	Orders cancellation after the reminders		(28)		
Patient-related	Patient complication			(28), (39), (41)	
	Patient disposition	(34)			
	LOS			(34)	
	Mortality rate	(34)			

*This study used three different CDSS intervention; two of which had positive impact and one of which had negative impact