Chapter 13
Clinical Decision Support: The Experience at Brigham and Women's Hospital/Partners HealthCare

Paul Varghese, Adam Wright, Jan Marie Andersen, Eileen I. Yoshida, and David W. Bates

Abstract In this chapter, we review clinical decision support systems (CDSS) at Brigham and Women's Hospital (BWH), including design, implementation, and evaluation. BWH has over 40 years active experience in the development of clinical information systems. Here we focus specifically on BWH's work in assessing the impact of CDSS in critical areas of patient safety, quality, and cost outcomes, and offer generalizable lessons for current and future applications of CDSS. CDSS examined include both inpatient and outpatient systems, medication related, laboratory and radiology decision support as well as documentation-related CDSS, clinical reminders, and patient-centric applications. Also included are descriptions of studies on the impact on the user and cost-effectiveness of CDSS.

Keywords Clinical decision support • Brigham and Women's Hospital • Partners healthcare • Clinical reminders • Patient-centric • Cost-effectiveness

P. Varghese, M.D. • A. Wright, M.S., Ph.D. (✉) • D.W. Bates, M.D., M.Sc.
Clinical and Quality Analysis, Information Systems, Partners HealthCare System, Inc.,
93 Worcester Street, Suite 201, Wellesley, MA 02481, USA

Division of General Internal Medicine and Primary Care, Brigham and Women's Hospital,
1620 Tremont Street - OBC-3, Boston, MA 02120, USA

Department of Medicine, Harvard Medical School,
75 Francis Street, Boston, MA 02115, USA
e-mail: paul_varghese@hms.harvard.edu; awright@bwh.harvard.edu; dbates@partners.org

J.M. Andersen, M.A.
Clinical and Quality Analysis, Information Systems, Partners HealthCare System, Inc.,
93 Worcester Street, Suite 201, Wellesley, MA 02481, USA

Division of General Internal Medicine and Primary Care, Brigham and Women's Hospital,
1620 Tremont Street - OBC-3, Boston, MA 02120, USA
e-mail: jmandersen@partners.org

E.I. Yoshida, B.Sc.Phm., M.B.A.
Partners eCare, Partners Healthcare System Inc.,
93 Worcester Street, Wellesley, MA 02481, USA
e-mail: eyoshida1@partners.org

E.S. Berner (ed.), *Clinical Decision Support Systems*, Health Informatics,
DOI 10.1007/978-3-319-31913-1_13

13.1 Background

Located in Boston, MA and with origins dating to 1832, BWH is a non-profit 793-bed facility, providing clinical practice ranging from primary care to tertiary/quaternary care. In 2014, BWH had approximately 46,000 inpatient admissions, over 4.2 million patient visits and 59,000 emergency department visits. In 1994, BWH joined with the Massachusetts General Hospital (MGH) to found Partners HealthCare System, which in 20 years has grown to include nine hospitals and five community health centers as well as a managed care organization and physician network [1].

A major teaching hospital for Harvard Medical School, BWH has done leading research in clinical medicine, population health, and health services research and this has directly shaped its approach in implementing and evaluating health information technology (HIT), particularly with clinical information systems for computerized provider order entry (CPOE) and Clinical Decision Support (CDS).

The key systems developed and deployed are the *Brigham Integrated Computing System* (*BICS*) and the *Longitudinal Medical Record* (*LMR*), both of which have been in use at BWH for close to 20 years. In this chapter, we review clinical decision support systems (CDSS) at BWH, including design, implementation, and evaluation.

13.1.1 Brigham Integrated Computing System (BICS)

In 1984, BWH initiated development of its clinical information system, the Brigham Integrated Computing System (BICS). Richard Nesson, MD, CEO of BWH at the time, had previously been instrumental in one of the first implementations of an automated medical record system (COSTAR) to support patient care, quality assurance and billing at Harvard Community Health Plan [2]. With this formative influence, BWH leadership moved to build upon technology developed at neighboring Boston hospitals to further improve quality of care and patient safety.

The predecessor to BICS began in 1976 as a direct port of the clinical information system created by Howard Bleich, MD and Warner Slack, MD, at the then Beth Israel Hospital in Boston [3]. Based upon a MUMPS database (a development of the Laboratory of Computer Science at MGH) and utilizing client-server architecture, BICS initially provided review access to clinical reports including lab values, imaging and pathology reports. However, the central vision of BICS was well-established from its inception: transition information systems from being a passive repository of clinical data to playing an active role contributing to improved quality of care and reduction of both adverse events and cost [1].

To fulfill this objective, BICS was expanded to include sophisticated order entry, under the leadership of John Glaser, PhD, BWH's chief information officer and Jonathan Teich, MD, PhD, the system's lead architect. The BICS design philosophy emphasized: (1) *broad content* using coded/structured information (building the root data for alerts and recommendations); (2) *workflow support*, where screens

display relevant contextual data useful to a particular clinical scenario; (3) *clinical decision support*, providing appropriate interventions to modify current processes of care; (4) *efficient communication*, to bring to disparate care team members urgent data reflected in real-time display; (5) *education*, so clinicians have context for CDS recommended interventions; and (6) *added value*, where advanced services provide users with greater efficiency and satisfaction [1].

Later expansion of features included: alerts for panic-value labs (1991); automatic email notifications of a patient's emergency department visits to a primary care provider (1992); and a clinical reference system ("Handbook") (1992). To improve transitions of care, BICS incorporated both cross-coverage lists (continuously tracking relationship between provider coverage and patients) and automatically generating sign-out communications (1993) [1].

In 1993–1994, two significant developments set the foundation for the long-term success of BICS: the introduction of CPOE within BICS, providing a substrate to influence treatment plans at the time of creation through decision support; and deployment of a flexible, configurable rule-based Event Engine, which provided a platform for monitoring data in real time and notifying physicians [1].

CPOE used a text-mode interface with structured windows. Screens were designed specifically for each type of order, and were often enhanced with relevant clinical information. For example, a digoxin order screen presented the physician with the latest renal function values, serum potassium value and digoxin level; blood product orders displayed transfusion restrictions and results of last crossmatch. In 1995, order sets, starting with chemotherapy, were deployed [1].

The Event Engine system was created for the purpose of detecting important events, testing them for importance to the patient, and rapidly conveying enough information to the caregiver that swift action could be taken in response. This was made possible by the combination of a logic-triggering system which detected new clinical data which might trigger a rule, a dispatcher which directed the data to the proper logic, an inference engine which evaluates logic states defined using a collection of standard logic primitives, a notification system to quickly contact clinicians (by text page or alert), and an action-item processor which made taking action on alerts straightforward [1].

With these functions in place, BICS had the essential elements as a platform for successful CDSS, allowing for the steady expansion of functionality and remaining in continuous use for over 20 years, with transitions from Visual Basic front end to a full Windows environment. BICS received Office of the National Coordinator-Authorized Certification Body (ONC-ACB) certification in 2014.

Of note, BICS was designed for use in both the inpatient and ambulatory settings, with BICS ambulatory record module ("MiniAmb") implemented in 1990. MiniAmb contained problem lists, medications, allergies, vital signs and progress notes (free text entry or transcription from dictation), along with a health maintenance section which organized key data, including cholesterol values and Pap smear results to support management [1].

With the creation of Partners HealthCare, the founding hospitals of BWH and MGH confronted the challenge of unifying different clinical information systems.

Each hospital would continue with its own inpatient information systems, but would adopt a common ambulatory medical record, built upon the success of MiniAmb and called the Longitudinal Medical Record (LMR).

13.1.2 Longitudinal Medical Record (LMR)

The Longitudinal Medical Record (LMR) was implemented in 1997 as a full-featured electronic health record (EHR) in all Partners HealthCare ambulatory settings. The LMR includes notes for primary care and subspecialties, coded and uncoded problem lists, medication lists, coded allergies and results from laboratory tests and radiographic studies (drawn from a Partners-wide clinical data repository). The LMR provides facilities for e-prescribing and radiology ordering; however direct laboratory order entry is not supported. As described by Linder et al. the LMR implements a wide range of CDS, including "reminders for preventive services and chronic care management; medication monitoring; medication dosing alerts and medication alerts for drug-drug, drug-lab, and drug-condition and drug-allergy interactions" [4]. The LMR also has a registry and quality management function, which provides panel management tools which draw from a data warehouse [4].

The LMR, now web-based, was first certified by the Certification Commission for Healthcare Information Technology (CCHIT) as a complete ambulatory EHR in 2007, with subsequent ONC-ACB certifications in 2014 (see Fig. 13.1 for a screenshot from the LMR).

Since the initial implementation of BICS and the LMR, BWH has been motivated by the belief that CDSS via EHRs are the means to improved performance in a wide range of patient care domains: clinical outcomes, utilization and performance measures, and in particular, patient safety. What follows next are the salient observations from a series of studies evaluating CDSS impact in these areas, focused in the inpatient and ambulatory settings.

13.2 Clinical Decision Support: Inpatient Applications and Assessment

13.2.1 Medication-Related Decision Support

General Applications

BICS supports medication ordering and was designed to reduce errors and encourage appropriate and cost-effective ordering. Interventions at appropriate points during the ordering process display warnings, reminders, and/or suggested alternatives related to the ordered medication [5].

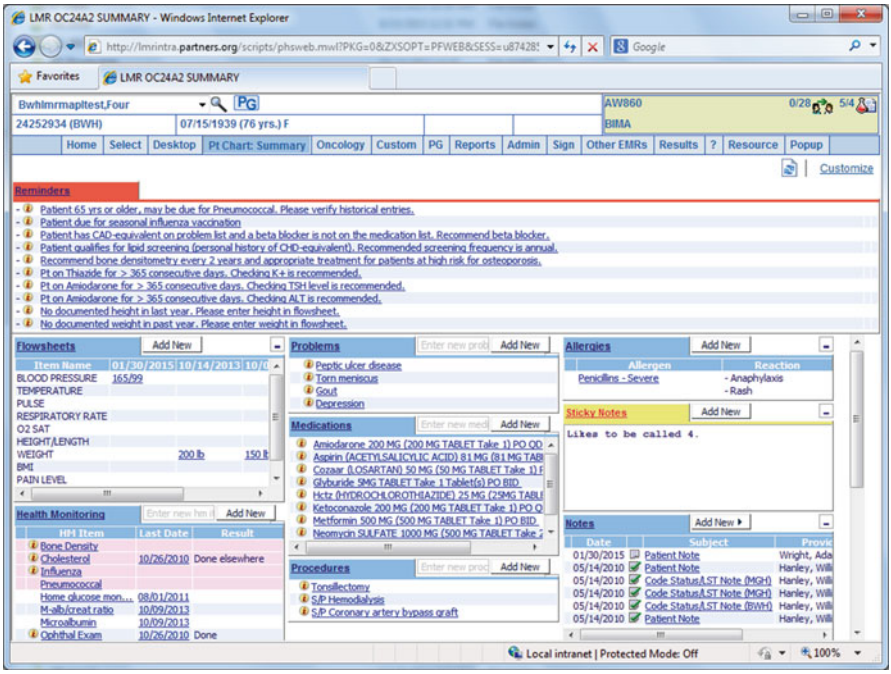

Fig. 13.1 Screenshot of LMR

When ordering a medication for a patient, the system suggests a patient-specific dose and frequency of medication to the prescriber. In addition, common CDS features such as drug-allergy, drug-drug interactions, duplicate medications, and possible alternative medications for the given clinical situation are also presented. All of these CDS tools have been developed using a process of iterative refinement [5].

After an initial order, consequent order recommendations are triggered which alert the physician to possible additional orders that should follow. For example, after a patient is placed on bed rest, BICS checks for preexisting heparin orders and, if none are found, BICS will suggest that an order be placed for subcutaneous heparin to prevent deep vein thrombosis [5].

Evaluation of medication-related interventions showed positive impact on medication selection (improvement in the use of lower-cost histamine$_2$-blocking agents); dosage guidance (reduction in dosages exceeding highest recommended dose for all medications); frequency recommendations (increase in ondansetron TID vs. QID dosing); and consequent orders (a doubling of heparin orders placed in conjunction with bed rest orders) [5].

Reduction of Adverse Drug Events

In 1995, BWH produced seminal studies in the systems analysis and epidemiology of actual and potential adverse drug events (ADEs) in hospitalized patients [6,7]. These studies determined that 42 % of serious or life-threatening ADEs were found to be preventable, with 52 % of these occurring at the ordering stage. A consequence of these results was a sharp focus on using and evaluating BICS as a means of reducing the frequency of ADEs.

An initial study established that BICS, with simple medication-ordering decision support (drug names from standard lists, default drug dosages, and limited checks for drug-allergy, drug-drug and drug-laboratory interactions), reduced serious ADEs by 55 % [8]. A follow-up study, which was performed after iterative improvement of drug-allergy and drug-drug interaction checking, showed an 88 % reduction of serious ADEs and an 81 % reduction in the overall medication error rate [9].

Anticipatory Medication Decision Support

In 1996, BWH implemented a CDS module (Nephros) to provide dosing recommendations for a subset of drugs which are renally cleared or nephrotoxic. In Nephros, when patients with decreased renal function (as estimated using the Cockcroft-Gault equation), are prescribed these potentially dangerous medications, a recommendation of a modified dose list (dose and frequency) is triggered and/or a recommendation of an alternative medication. When studied in a controlled trial, this functionality was found to increase the rate of appropriate prescriptions (59 % vs. 35 %) in patients with impaired renal function, and to decrease a patient's length of stay (4.3 vs. 4.5 days) [10].

Subsequently, a companion CDS module (Gerios) was developed to deliver evidence-based prescribing recommendations for psychotropic medications in hospitalized geriatric patients (age >65), with the goal of better drug selection and reduction in initial dosing where appropriate. For these medications, a modified dose list (dose and frequency) is presented and/or an alternative medication is recommended. In addition, in elderly patients with decreased renal function, who are prescribed a medication listed in both knowledge bases, the Nephros and Gerios CDSS work together and will only present one recommendation to the user.

In a controlled trial, orders written for patients in the cohort receiving the recommendations were (1) more likely to be at the recommended daily dose (29 % vs. 19 %), (2) less likely to have a tenfold misdose (2.8 % vs. 5.0 %), and (3) less likely to be for non-recommended drugs (7.6 % vs. 10.8 % of total orders). Additionally, patients in the cohort who got the CDS intervention had fewer falls in the hospital (0.28 vs. 0.64 falls per 100 patient-days). The recommendations were not found to have any effect on hospital length of stay or days of altered mental status [11]. Since the study, the knowledge base continues to be updated using the Beers criteria.

Medication-Specific Decision Support

BWH has evaluated the implementation of medication-specific recommendations as interventions. In a 1998 randomized control trial, vancomycin use guidelines based upon the Centers for Disease Control and Prevention's (CDC) recommendations were incorporated into BICS, to examine the effect on Vancomycin overuse. Physicians receiving the intervention placed 32 % fewer orders than physicians in the control group. Vancomycin orders were initiated or renewed for 28 % fewer patients in the intervention group. Compared with the control group, patients of the intervention physicians received courses of Vancomycin that were shorter by 36 % [12].

In another study focusing on the high utilization of the high-cost medication human growth hormone in the surgical intensive care unit, a targeted guideline requiring the indication and the tracking of the ordering provider was implemented. This seemingly small intervention reduced human growth hormone use by one-third [13].

13.2.2 Laboratory-Related Decision Support

BWH has evaluated the impact of CDS interventions to improve utilization and efficacy of clinical laboratory testing, with the studies showing a range of success.

Display of Charges at Test Ordering

In a randomized clinical trial, charges for 19 commonly ordered clinical laboratory tests and cumulative totals were displayed at the time the tests were ordered. This simple intervention had little or no impact on the number of tests ordered. Of note, although the results of the intervention were not statistically significant, they did show a trend toward fewer tests, in particular for more expensive tests. Given projected cost savings for this trend, the display of charges was continued after the conclusion of the trial [14].

Reduction in Redundant Testing

A 1998 utilization study at BWH identified that 9 % of ten common clinical laboratory tests were ordered in a redundant manner and potentially could be eliminated by CDSS, resulting in the projected reduction of $930,000 in charges [15].

A subsequent follow-up intervention to reduce redundant testing was evaluated in a 1999 randomized control trial. Tests targeted included a serum chemistry panel, therapeutic medication level monitoring for six medications, and three microbiology cultures. When a physician placed an order for a test that had previously been

ordered within a given, test-specific interval, an alert was shown stating that the test had been performed recently – including the result, if available – or was pending. The default response after a reminder was delivered was cancellation of the redundant test order, but physicians could continue with the order if they so chose. With this intervention, the proportion of redundant tests that were performed was lowered from 51 % to 27 % [16].

However, the overall effect on costs was smaller than expected for three reasons: (1) over half (56 %) of the redundant tests did not have an associated computer order (the laboratory system at BWH was not directly integrated with the order entry system, so tests could be performed without orders), (2) not all tests were screened for redundancy; approximately half of computer-ordered tests were ordered using order sets, which were omitted from the algorithm, and (3) almost one third (31 %) of reminders were overridden, while the original estimate assumed 100 % of detected redundant orders would be canceled [16].

In a subsequent 2003 randomized clinical trial, BWH targeted potentially redundant therapeutic monitoring of anti-epileptic medication levels, primarily focused on reducing orders for test of serum drug levels which were placed before the medication level was expected to have reached a steady state. Additionally, the CDS intervention provided education aimed at increasing the appropriateness of non-redundant monitoring of drug levels. Following implementation of the CDSS, 13 % of all anti-epileptic drug tests ordered were cancelled and inappropriate repeat testing before steady state decreased from 54 % to 14.6 %. The total volume of anti-epileptic drug level testing decreased by 19.5 % [17].

Tests Pending at Discharge

Discharge from the hospital is a particularly dangerous time for communication failures and ambiguity about responsibility. In 2005, BWH research identified that 41 % of patients were discharged with tests pending at discharge (TPADs), but inpatient/primary care providers were aware of only 38 % of these pending tests [18]. To better manage TPADs, BWH developed an automated email system to notify the both the responsible inpatient-attending physician at discharge and the patient's primary care provider (PCP) of the final results of TPADs [19, 20].

The TPAD notification system was evaluated using a cluster-randomized controlled trial, investigating the impact on physician awareness of TPAD results and surveying physicians to assess overall satisfaction with the system. Attending physicians in the intervention group were significantly more aware of TPAD results than those in the control group: 76 % vs. 38 %. Intervention PCPs showed a slightly less dramatic though still significant increase in awareness of 57 % versus 33 % of control PCPs. Intervention attending physicians were more aware of actionable TPAD results, showing a level of awareness of these results of 59 % compared to 29 % in control attending physicians [21].

13.2.3 Radiology-Related Decision Support

Appropriateness of Ordered Studies

Effectiveness of CDSS interventions to improve utilization of radiology tests at BWH has progressed iteratively: as the CDSS has added more feedback information (e.g. pretest probabilities) to the providers, there has been greater impact on the appropriateness of test ordering.

In the initial implementation of BICS, the CDSS for radiology functioned in a critiquing mode. Providers were required to input coded patient condition information and test indications for radiology orders, which were used to provide feedback to providers on the appropriateness of the test ordered and suggested alternatives. An early study in 1997 showed limited acceptance of suggestions to cancel inappropriate abdominal radiographs (3–4 %). The addition of recommendations for alternative testing only resulted in 45 % compliance [22].

However, more recent evaluation of radiology CDSS interventions for CT orders has shown significant impact. By informing providers about the pretest probability of pulmonary embolism (PE) (based on clinical suspicion level and D-dimer status), orders for pulmonary angiograms by CT decreased 20 % for emergency department (ED) patients and by 12.3 % for hospitalized patients [23, 24]. Including guidelines for appropriate use of head CT in ED patients with minor traumatic brain injury led to a 56 % increase in guideline adherence [25].

Notification About Critical Radiology Results

In 2007, building on national patient safety initiatives to promote optimal communication of critical test results, BWH undertook a comprehensive effort to address timely delivery and assured receipt of critical radiology findings in the inpatient setting [26]. The process identified a need to develop an automated closed-loop notification system for critical results, leading to the creation of the Alert Notification of Critical Results (ANCR) tool, a web-based, open-source system which was integrated within the BICS environment in 2010.

ANCR allowed radiologists to communicate critical results through synchronous (e.g. paging) and asynchronous (e.g. secure HIPAA-compliant email) mechanisms with secure, auditable, web-enabled acknowledgement by ordering providers. A 4-year assessment of the ANCR system's impact on adherence to BWH critical results policy revealed adherence increased from 91.3 to 95 %, with a ninefold increase in critical results communicated via the system. Sixty percent of less urgent but still critical results were delivered and acknowledged via the ANCR system's non-interruptive communication (email) [27].

13.2.4 Transition of Care Support

Early in its implementation (1992–1993), BICS functionality was extended to support physician cross-coverage hand-offs of patient responsibilities, via Coverage List and Sign-out applications. CDS applications that detect significant clinical events can use the coverage list to route notifications to the responsible team member. The Sign-out application provides residents with abstracted patient lists that include medications, notable recent laboratory tests, and code status, which can be printed out. A case-controlled study demonstrated that Sign-out served to eliminate the previously identified sixfold increase in risk of adverse events associated with cross-coverage times [28, 29].

13.2.5 Assessment of CPOE Impact on Users

CPOE implementation at BWH was evaluated for impact on providers' satisfaction and time. A 1996 survey study of physicians and nurses (medical and surgical) showed good overall satisfaction with CPOE, including embedded CDS [30]. Formal assessment of CPOE's impact on productivity involved a prospective time-motion study. The study found that interns using CPOE spent 9.0 % of their time entering orders, compared to 2.1 % of their time before adoption. However, other features of CPOE yielded a 2 % time savings, making the net difference only 5 %. The interns' use of CPOE, however, saved time for other disciplines, including pharmacy and nursing [31].

13.3 Clinical Decision Support: Ambulatory Applications and Assessment

Many of the successful CDS interventions developed in the inpatient setting are also used in the outpatient systems at BWH.

13.3.1 Ambulatory Medication Decision Support

Medication-related CDSS in the LMR mirrors and extends the functionality of BICS in the inpatient setting. With iterative development, LMR offers alerts and recommendations for drug-allergy conflicts; drug-lab checks; drug-disease checks; drug-pregnancy checks; drug-drug interaction (DDI); drug and therapeutic duplication checks; and drug utilization costs. LMR also incorporates the Nephros

(renal-based dosing) and Gerios (age-based dosing) systems previously described in this chapter.

BWH has evaluated the impact and utility of these types of alerts in the outpatient setting. To reduce alert fatigue, BWH developed highly targeted knowledge bases which contain only the most clinically relevant drug contraindications in the ambulatory setting. Alerts are divided into three tiers: "fatal or life-threatening interactions" (Level 1), "undesirable interactions with the potential for serious injury" (Level 2) and possible undesirable interactions where drug should be used with caution (Level 3) [32].

These tiers affect the presentation of DDI alerts in the system. Level 1 alerts are hard stops – clinicians cannot proceed without eliminating one of the interacting drugs. High severity alerts (Level 2) are interruptive, requiring clinicians to provide a reason before proceeding. The most common alerts, Level 3, are informational – a warning is shown on the ordering screen, but no reason for override is required, and no additional clicks are necessary [32].

A 6-month study of this tiered DDI system demonstrated that only 29 % were in the higher categories (Levels 1 and 2), with a 67 % acceptance rate (order either cancelled or modified) – a much higher acceptance rate than reported in other systems, suggesting that this high acceptance was due to limiting alert burden via selective knowledge base and minimizing workflow interruptions [33].

This particular BWH experience (developing selective knowledge bases for high-severity/interruptive DDI and non-interruptive DDI classifications) has subsequently served as the basis for consensus-based recommendations for standardized lists of DDI for incorporation in EHRs [34, 35].

Subsequent research to improve acceptance of alerts and reduce alert fatigue has better characterized the nature of outpatient alert overrides. A study of 157,483 CDS alerts in a 3-year period found providers overrode 52.6 % of alerts. Formulary substitutions had an 85.0 % override rate, followed by age-based recommendations with an override rate of 79.0 %, renal dosage recommendations showing a 78.0 % override rate, and allergies at 77.4 % of alerts overridden. Half of the total overrides were evaluated as clinically appropriate – drug-allergy alerts, drug duplication and therapeutic class duplication warnings and formulary-related alerts were particularly likely to be subject to appropriate overrides [36].

13.3.2 Laboratory-Related Decision Support

Although LMR does not support computerized laboratory ordering for ambulatory patients, a dedicated module within LMR, Results Manager (RM), provides CDS capabilities for laboratory result management. RM facilitates test result follow-up by collecting, organizing, and prioritizing these results. Functionality in RM includes sorting results by degree of abnormality, multi-lingual templates for

sending letters to patients about lab results and guideline-based CDS about appropriate follow-up and management of abnormal results, along with reminders for repeat testing where indicated [37].

13.3.3 Radiology-Related Decision Support

Ambulatory radiology CPOE was first implemented at BWH in primary care offices in 2000, with the adoption of a web-enabled commercial product (Precipio) from Medicalis Corporation (San Francisco, CA) – the company was a joint venture between BWH and Harvard Medical School. The commercial product is fully integrated as a module within the LMR [38].

Orders are created from predetermined structured menus and controlled vocabularies to specify a requested imaging procedure and clinical indications. Clinicians are provided recommendations on diagnostic strategy based on the patient's clinical context and presentation data. For example, an order for an abdominal radiograph in a patient with suspected appendicitis triggers a "low-utility" message with a recommendation for a higher yield examination. Clinicians may choose to cancel the request or proceed with the order [38].

Targeted CDS interventions included alerting ordering providers to potentially redundant CT studies, resulting in 6 % cancellation of orders [39], and recommendations against ordering MRI imaging for patients with low back pain, resulting in 30 % reduction in orders [40].

13.3.4 Clinical Reminders

The LMR has a reminder system to alert clinicians to guideline-based screening, and preventive interventions. While these are well received by physicians, evaluation of the efficacy of reminders in improving care has demonstrated mixed results.

A 2005 randomized trial of LMR reminders for diabetic care (five total) and coronary artery disease care (four total) showed significant improvements in overall compliance with recommended care when physicians were shown reminders; however, the effect of individual reminders was variable [41].

A 2008 study provided suggestions for evidence-based laboratory monitoring for chronic medications, including testing for liver and kidney function and monitoring of drug levels. The study found no effect of the intervention, perhaps because the alerts were not actionable [42].

In 2011, a study investigated a set of actionable reminders for screening and monitoring, which also showed no effect. The limited effect of these reminders was thought to be strongly related to adoption of the reminders – notably, 79 % of responding physicians were either unaware of the functionality or almost never used it [43].

13.3.5 Documentation-Related Decision Support

Researchers at BWH led the development of the Smart Form, a clinical workflow tool integrating condition specific templates and knowledge-based orders to facilitate simultaneous clinical documentation, structured data capture, and actionable decision support [44]. Pilot studies showed modest improvement in the management and treatment of acute respiratory infection [45] and diabetes/coronary artery disease [46]; however, in both studies, overall physician use of the forms was low, and was likely impacted by the limited integration into LMR that required separate manual action by the users to initiate the form.

13.3.6 Problem-List Decision Support

Primary care providers at BWH do the majority of problem list maintenance (despite a policy of shared responsibility with specialists) [47]. To support them in this work, BWH developed a series of inference rules which identify potentially undocumented potential patient problems for 17 target conditions by evaluating a range of structured data, including laboratory results, medications, ICD-9 diagnosis codes and vital signs [48]. A randomized trial of an intervention implementing these inference rules as alerts suggesting problems resulted in a threefold increase in problem documentation for study conditions – in fact, in the intervention arm, 70.4 % of all study problems were added to the list via alerts [49].

13.3.7 Assessment of Ambulatory EHR Impact on Users

The incremental implementation of the LMR throughout the Partners HealthCare ambulatory clinics provided opportunity to assess impact on productivity. A formal time-motion study found that using the LMR did not require additional physician time to complete a primary care session compared to a clinic's existing paper-based system, nor were significant increases in administrative duties for physicians observed [50].

13.3.8 Patient-Centric Applications

In 2002, LMR incorporated a personal health record (PHR) called Patient Gateway (PG), which allowed patients web-based viewing of the contents of their medical record (medications, allergies, lab values) and on-line communication with their providers [51].

With the primary goal of improving patient experience and engagement, the PG was also intended to support quality of care improvements. A prospective, randomized trial of a PHR intervention including health screening questions, medication history documentation and diabetes management was carried out at BWH [52]. For the intervention arm, patients were given the opportunity to view/interact with components of their EHR and create "e-Journals" of information to be updated and/or addressed with their primary care doctors.

The study demonstrated the intervention group patients had increased rates of diabetes-related medication adjustment [53]. Providing direct-to-patient health maintenance reminders increased the rates of some types of preventive care (mammography and influenza vaccinations) [54]. Additionally, the intervention reduced potentially harmful medication discrepancies [55].

13.4 Clinical Decision Support: Cost-Effectiveness

Investigators at BWH have undertaken evaluation of the cost-effectiveness of implementing its EHR with CPOE/CDS, in both the inpatient and ambulatory settings. Between 1992 and 2003, BWH's total cost for developing, implementing and maintaining its inpatient CPOE system were $11.8 million, compared to savings of $28.5 million (largely due to reduction in harm from the renal dosing system, as well as increased efficiency for nurses and other drug-related CDS) [56].

Cost-effectiveness evaluation of the LMR also found significant financial benefit, estimated at $86,400 per provider over a 5 year period, driven largely by savings in drug costs, reduction in unnecessary imaging and better billing [57].

13.5 Overarching Lessons

In 2003, Bates et al. published "The Ten Commandments of Clinical Decision Support" and it remains a salient summary of the lessons learned during BWH experience with the implementation of CDSS [13]. The 'Ten Commandments' as identified in the paper are:

1. Speed Is Everything
2. Anticipate Needs and Deliver in Real Time
3. Fit into the User's Workflow
4. Little Things Can Make a Big Difference
5. Recognize that Physicians Will Strongly Resist Stopping
6. Changing Direction Is Easier than Stopping
7. Simple Interventions Work Best
8. Ask for Additional Information Only When You Really Need It
9. Monitor Impact, Get Feedback, and Respond
10. Manage and Maintain Your Knowledge-based Systems [13].

13.6 Future Directions

In 2013, BWH charted a new direction for CDSS and the EHR when Partners HealthCare made the transformative decision to move away from its long-standing model of self-developing clinical information systems in favor of a commercial EHR, selecting the Epic system. A key goal of this program, dubbed Partners eCare, is better integration across the large Partners HealthCare delivery network.

In May 2015, BWH was the first Partners site to go live on the Partners eCare Epic clinical system with a big-bang implementation in both inpatient and outpatient settings. Although not all the previously developed decision support could be deployed initially, the CDSS have all been inventoried, and with the strong commitment of BWH leadership, the intent is to implement additional CDSS as resources allow. Thus, BWH's years of experience in developing clinical information systems will now be applied to developing/implementing CDS features within this new environment. BWH researchers see new opportunities to innovate and to perform the rigorous systematic evaluation of CDS safety and efficacy they have practiced for the last 40 years.

References

1. Teich JM, Glaser JP, Beckley RF, Aranow M, Bates DW, Kuperman GJ, et al. The Brigham integrated computing system (BICS): advanced clinical systems in an academic hospital environment. Int J Med Inform. 1999;54(3):197–208.
2. Grossman JH, Barnett GO, Koepsell TD, Nesson HR, Dorsey JL, Phillips RR. An automated medical record system. JAMA. 1973;224(12):1616–21.
3. Bleich HL, Beckley RF, Horowitz GL, Jackson JD, Moody ES, Franklin C, et al. Clinical computing in a teaching hospital. N Engl J Med. 1985;312(12):756–64.
4. Linder JA, Schnipper JL, Middleton B. Method of electronic health record documentation and quality of primary care. J Am Med Inform Assoc: JAMIA. 2012;19(6):1019–24.
5. Teich JM, Merchia PR, Schmiz JL, Kuperman GJ, Spurr CD, Bates DW. Effects of computerized physician order entry on prescribing practices. Arch Intern Med. 2000;160(18):2741–7.
6. Leape LL, Bates DW, Cullen DJ, Cooper J, Demonaco HJ, Gallivan T, et al. Systems analysis of adverse drug events. ADE Prevention Study Group. JAMA. 1995;274(1):35–43.
7. Bates DW, Cullen DJ, Laird N, Petersen LA, Small SD, Servi D, et al. Incidence of adverse drug events and potential adverse drug events. Implications for prevention. ADE Prevention Study Group. JAMA. 1995;274(1):29–34.
8. Bates DW, Leape LL, Cullen DJ, Laird N, Petersen LA, Teich JM, et al. Effect of computerized physician order entry and a team intervention on prevention of serious medication errors. JAMA. 1998;280(15):1311–6.
9. Bates DW, Teich JM, Lee J, Seger D, Kuperman GJ, Ma'Luf N, et al. The impact of computerized physician order entry on medication error prevention. J Am Med Inform Assoc. 1999;6(4):313–21.
10. Chertow GM, Lee J, Kuperman GJ, Burdick E, Horsky J, Seger DL, et al. Guided medication dosing for inpatients with renal insufficiency. JAMA. 2001;286(22):2839–44.
11. Peterson JF, Kuperman GJ, Shek C, Patel M, Avorn J, Bates DW. Guided prescription of psychotropic medications for geriatric inpatients. Arch Intern Med. 2005;165(7):802–7.

12. Shojania KG, Yokoe D, Platt R, Fiskio J, Ma'luf N, Bates DW. Reducing vancomycin use utilizing a computer guideline: results of a randomized controlled trial. J Am Med Inform Assoc. 1998;5(6):554–62.
13. Bates DW, Kuperman GJ, Wang S, Gandhi T, Kittler A, Volk L, et al. Ten commandments for effective clinical decision support: making the practice of evidence-based medicine a reality. J Am Med Inform Assoc. 2003;10(6):523–30.
14. Bates DW. Does the computerized display of charges affect inpatient ancillary test utilization? Arch Intern Med. 1997;157(21):2501.
15. Bates DW, Boyle DL, Rittenberg E, Kuperman GJ, Ma'Luf N, Menkin V, et al. What proportion of common diagnostic tests appear redundant? Am J Med. 1998;104(4):361–8.
16. Bates DW, Kuperman GJ, Rittenberg E, Teich JM, Fiskio J, Ma'luf N, et al. A randomized trial of a computer-based intervention to reduce utilization of redundant laboratory tests. Am J Med. 1999;106(2):144–50.
17. Chen P, Tanasijevic MJ, Schoenenberger RA, Fiskio J, Kuperman GJ, Bates DW. A computer-based intervention for improving the appropriateness of antiepileptic drug level monitoring. Am J Clin Pathol. 2003;119(3):432–8.
18. Roy CL, Poon EG, Karson AS, Ladak-Merchant Z, Johnson RE, Maviglia SM, et al. Patient safety concerns arising from test results that return after hospital discharge. Ann Intern Med. 2005;143(2):121–8.
19. Dalal AK, Poon EG, Karson AS, Gandhi TK, Roy CL. Lessons learned from implementation of a computerized application for pending tests at hospital discharge. J Hosp Med. 2011;6(1):16–21.
20. Dalal AK, Schnipper JL, Poon EG, Williams DH, Rossi-Roh K, Macleay A, et al. Design and implementation of an automated email notification system for results of tests pending at discharge. J Am Med Inform Assoc: JAMIA. 2012;19(4):523–8.
21. Dalal AK, Roy CL, Poon EG, Williams DH, Nolido N, Yoon C, et al. Impact of an automated email notification system for results of tests pending at discharge: a cluster-randomized controlled trial. J Am Med Inform Assoc. 2014;21(3):473–80.
22. Harpole LH, Khorasani R, Fiskio J, Kuperman GJ, Bates DW. Automated evidence-based critiquing of orders for abdominal radiographs: impact on utilization and appropriateness. J Am Med Inform Assoc. 1997;4(6):511–21.
23. Raja AS, Ip IK, Prevedello LM, Sodickson AD, Farkas C, Zane RD, et al. Effect of computerized clinical decision support on the use and yield of CT pulmonary angiography in the emergency department. Radiology. 2012;262(2):468–74.
24. Dunne RM, Ip IK, Abbett S, Gershanik EF, Raja AS, Hunsaker A, et al. Effect of evidence-based clinical decision support on the use and yield of CT pulmonary angiographic imaging in hospitalized patients. Radiology. 2015;276(1):167–74.
25. Ip IK, Raja AS, Gupta A, Andruchow J, Sodickson A, Khorasani R. Impact of clinical decision support on head computed tomography use in patients with mild traumatic brain injury in the ED. Am J Emerg Med. 2015;33(3):320–5.
26. Anthony SG, Prevedello LM, Damiano MM, Gandhi TK, Doubilet PM, Seltzer SE, et al. Impact of a 4-year quality improvement initiative to improve communication of critical imaging test results. Radiology. 2011;259(3):802–7.
27. Lacson R, Prevedello LM, Andriole KP, O'Connor SD, Roy C, Gandhi T, et al. Four-year impact of an alert notification system on closed-loop communication of critical test results. AJR Am J Roentgenol. 2014;203(5):933–8.
28. Hiltz FL, Teich JM. Coverage list: a provider-patient database supporting advanced hospital information services. Proc Annu Symp Comput Appl Med Care. 1994;809–13.
29. Petersen LA, Orav EJ, Teich JM, O'Neil AC, Brennan TA. Using a computerized sign-out program to improve continuity of inpatient care and prevent adverse events. Jt Comm J Qual Improv. 1998;24(2):77–87.
30. Lee F, Teich JM, Spurr CD, Bates DW. Implementation of physician order entry: user satisfaction and self-reported usage patterns. J Am Med Inform Assoc. 1996;3(1):42–55.

31. Shu K, Boyle D, Spurr C, Horsky J, Heiman H, O'Connor P, et al. Comparison of time spent writing orders on paper with computerized physician order entry. Stud Health Technol Inform. 2001;84(Pt 2):1207–11.
32. Yu DT, Seger DL, Lasser KE, Karson AS, Fiskio JM, Seger AC, et al. Impact of implementing alerts about medication black-box warnings in electronic health records. Pharmacoepidemiol Drug Saf. 2011;20(2):192–202.
33. Shah NR, Seger AC, Seger DL, Fiskio JM, Kuperman GJ, Blumenfeld B, et al. Improving acceptance of computerized prescribing alerts in ambulatory care. J Am Med Inform Assoc. 2006;13(1):5–11.
34. Phansalkar S, Desai AA, Bell D, Yoshida E, Doole J, Czochanski M, et al. High-priority drug-drug interactions for use in electronic health records. J Am Med Inform Assoc. 2012;19(5):735–43.
35. Phansalkar S, van der Sijs H, Tucker AD, Desai AA, Bell DS, Teich JM, et al. Drug-drug interactions that should be non-interruptive in order to reduce alert fatigue in electronic health records. J Am Med Inform Assoc. 2013;20(3):489–93.
36. Nanji KC, Slight SP, Seger DL, Cho I, Fiskio JM, Redden LM, et al. Overrides of medication-related clinical decision support alerts in outpatients. J Am Med Inform Assoc. 2014;21(3):487–91.
37. Poon EG, Wang SJ, Gandhi TK, Bates DW, Kuperman GJ. Design and implementation of a comprehensive outpatient results manager. J Biomed Inform. 2003;36(1–2):80–91.
38. Ip IK, Schneider LI, Hanson R, Marchello D, Hultman P, Viera M, et al. Adoption and meaningful use of computerized physician order entry with an integrated clinical decision support system for radiology: ten-year analysis in an urban teaching hospital. J Am Coll Radiol. 2012;9(2):129–36.
39. Wasser EJ, Prevedello LM, Sodickson A, Mar W, Khorasani R. Impact of a real-time computerized duplicate alert system on the utilization of computed tomography. JAMA Int Med. 2013;173(11):1024–6.
40. Ip IK, Gershanik EF, Schneider LI, Raja AS, Mar W, Seltzer S, et al. Impact of IT-enabled intervention on MRI use for back pain. Am J Med. 2014;127(6):512–8. e1.
41. Sequist TD, Gandhi TK, Karson AS, Fiskio JM, Bugbee D, Sperling M, et al. A randomized trial of electronic clinical reminders to improve quality of care for diabetes and coronary artery disease. J Am Med Inform Assoc. 2005;12(4):431–7.
42. Matheny ME, Sequist TD, Seger AC, Fiskio JM, Sperling M, Bugbee D, et al. A randomized trial of electronic clinical reminders to improve medication laboratory monitoring. J Am Med Inform Assoc. 2008;15(4):424–9.
43. El-Kareh RE, Gandhi TK, Poon EG, Newmark LP, Ungar J, Orav EJ, et al. Actionable reminders did not improve performance over passive reminders for overdue tests in the primary care setting. J Am Med Inform Assoc. 2011;18(2):160–3.
44. Schnipper JL, Linder JA, Palchuk MB, Einbinder JS, Li Q, Postilnik A, et al. "Smart forms" in an electronic medical record: documentation-based clinical decision support to improve disease management. J Am Med Inform Assoc. 2008;15(4):513–23.
45. Linder JA, Schnipper JL, Tsurikova R, Yu T, Volk LA, Melnikas AJ, et al. Documentation-based clinical decision support to improve antibiotic prescribing for acute respiratory infections in primary care: a cluster randomised controlled trial. Inform Prim Care. 2009;17(4):231–40.
46. Schnipper JL, Linder JA, Palchuk MB, Yu DT, McColgan KE, Volk LA, et al. Effects of documentation-based decision support on chronic disease management. Am J Manag Care. 2010;16(12 Suppl HIT):SP72–81.
47. Wright A, Feblowitz J, Maloney FL, Henkin S, Bates DW. Use of an electronic problem list by primary care providers and specialists. J Gen Intern Med. 2012;27(8):968–73.
48. Wright A, Pang J, Feblowitz JC, Maloney FL, Wilcox AR, Ramelson HZ, et al. A method and knowledge base for automated inference of patient problems from structured data in an electronic medical record. J Am Med Inform Assoc. 2011;18(6):859–67.

49. Wright A, Pang J, Feblowitz JC, Maloney FL, Wilcox AR, McLoughlin KS, et al. Improving completeness of electronic problem lists through clinical decision support: a randomized, controlled trial. J Am Med Inform Assoc. 2012;19(4):555–61.
50. Pizziferri L, Kittler AF, Volk LA, Honour MM, Gupta S, Wang S, et al. Primary care physician time utilization before and after implementation of an electronic health record: a time-motion study. J Biomed Inform. 2005;38(3):176–88.
51. Wald JS, Middleton B, Bloom A, Walmsley D, Gleason M, Nelson E, et al. A patient-controlled journal for an electronic medical record: issues and challenges. Stud Health Technol Inform. 2004;107(Pt 2):1166–70.
52. Wald JS, Businger A, Gandhi TK, Grant RW, Poon EG, Schnipper JL, et al. Implementing practice-linked pre-visit electronic journals in primary care: patient and physician use and satisfaction. J Am Med Inform Assoc. 2010;17(5):502–6.
53. Grant RW, Wald JS, Schnipper JL, Gandhi TK, Poon EG, Orav EJ, et al. Practice-linked online personal health records for type 2 diabetes mellitus: a randomized controlled trial. Arch Intern Med. 2008;168(16):1776–82.
54. Wright A, Poon EG, Wald J, Feblowitz J, Pang JE, Schnipper JL, et al. Randomized controlled trial of health maintenance reminders provided directly to patients through an electronic PHR. J Gen Intern Med. 2012;27(1):85–92.
55. Schnipper JL, Gandhi TK, Wald JS, Grant RW, Poon EG, Volk LA, et al. Effects of an online personal health record on medication accuracy and safety: a cluster-randomized trial. J Am Med Inform Assoc. 2012;19(5):728–34.
56. Kaushal R, Jha AK, Franz C, Glaser J, Shetty KD, Jaggi T, et al. Return on investment for a computerized physician order entry system. J Am Med Inform Assoc. 2006;13(3):261–6.
57. Wang SJ, Middleton B, Prosser LA, Bardon CG, Spurr CD, Carchidi PJ, et al. A cost-benefit analysis of electronic medical records in primary care. Am J Med. 2003;114(5):397–403.