WJCCM World Journal of Critical Care Medicine

Online Submissions: http://www.wjgnet.com/esps/
wjccm@wjgnet.com
doi:10.5492/wjccm.v2.i4.21

World J Crit Care Med 2013 November 4; 2(4): 21-28
ISSN 2220-3141 (online)

REVIEW

Computerized decision support in adult and pediatric critical care

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Received: June 14, 2013 **Revised:** August 2, 2013
Accepted: August 20, 2013
Published online: November 4, 2013

Abstract

Computerized decision support (CDS) is the most advanced form of clinical decision support available and has evolved with innovative technologies to provide meaningful assistance to medical professionals. Critical care clinicians are in unique environments where vast amounts of data are collected on individual patients, and where expedient and accurate decisions are paramount to the delivery of quality healthcare. Many CDS tools are in use today among adult and pediatric intensive care units as diagnostic aides, safety alerts, computerized protocols, and automated recommendations for management. Some CDS use have significantly decreased adverse events and improved costs when carefully implemented and properly operated. CDS tools integrated into electronic health records are also valuable to researchers providing rapid identification of eligible patients, streamlining data-gathering and analysis, and providing cohorts for study of rare and chronic diseases through data-warehousing. Although the need for human judgment in the daily care of critically ill patients has limited the study and realization of meaningful improvements in overall patient outcomes, CDS tools continue to evolve and integrate into the daily workflow of clinicians, and will likely provide advancements over time. Through novel technologies, CDS tools have vast potential for progression and will significantly impact the field of critical care and clinical research in the future.

Key words: Clinical decision support systems; Critical care; Computers; Computer-assisted decision making

Core tip: Computerized decision support (CDS) is increasingly utilized in both adult and pediatric critical care. Improvements in care have been shown in areas including guideline adherence and reduction of medical errors, but reports of meaningful improvements in patient outcome have been scarce to date. However, with technology improvements and widespread acceptance of tools, CDS has the potential to revolutionize critical care medicine with improved diagnosis, monitoring, risk prediction, and treatment. Improvements in multiple aspects of patient care through CDS tools can lead to better patient outcomes.

Williams CN, Bratton SL, Hirshberg EL. Computerized decision support in adult and pediatric critical care. *World J Crit Care Med* 2013; 2(4): 21-28 Available from: URL: http://www.wjgnet.com/2220-3141/full/v2/i4/21.htm DOI: http://dx.doi.org/10.5492/wjccm.v2.i4.21

INTRODUCTION

Decision support tools have been used by the medical profession for decades and evolved with technology to become largely computer based and widely accessible to all clinicians in the form of smart phone applications, web-based search engines, online references and journal access, and bedside tools incorporated into daily clinical practice. The potential for further advancements in biomedical informatics to improve healthcare quality is vast and increasingly studied at the patient care level and in research[1]. The goal of clinical decision support is to provide current and pertinent knowledge to clinicians to aid patient care at the exact time of care delivery[2]. Computerized technology provides the tools to facilitate timely delivery of this knowledge to bedside clinicians. Computerized decision support (CDS) systems have been implemented by hospitals internationally targeting important goals including improved diagnostic accuracy, error reduction, delivery of preventative care, and better patient outcomes[3]. As the field of medicine continues to increase in complexity, these tools are likely to become further integrated into patient care, as well as provide substantial resources for clinical research.

Intensive care unit (ICU) clinicians are in unique environments where vast amounts of information are collected and displayed by computerized systems, and where expedient, accurate diagnosis and treatment may profoundly affect quality of care and patient outcomes. ICU clinicians are tasked daily to manage large volumes of data from multiple sources and incorporate this data into patient-specific decisions. Given the unique position of ICU clinicians, CDS will likely become central to delivery of critical care in the coming years. However, inter-provider decision variability, lack of universal diagnostic and therapeutic protocols for many common diagnoses, and the demand for real-time individual variation at the bedside provide challenges for CDS design in critical care. In this paper, we give an overview of CDS history in clinical medicine, discuss different types of CDS tools, review some current applications in adult and pediatric critical care, address advantages and limitations to CDS tool use, and discuss the potential of CDS for critical care in the future.

HISTORY AND OVERVIEW OF COMPUTERIZED DECISION SUPPORT

CDS is the most efficient form of decision support and is designed to improve the quality of healthcare delivery, assist nurses and physicians in clinical decision making, and reduce variation[1,2]. CDS tools have evolved over time in both content and theoretical design for many healthcare related functions commonly used today: alert, diagnosis, reminder, suggestion, interpretation, prediction, critique, and assistance[4]. The concept of computer aided diagnosis in medicine was introduced as early as by Ledley *et al*[5]. Warner *et al*[6] presented a Bayesian theory based system for diagnosing congenital heart disease relying on inputted signs and symptoms. Design of CDS tools has evolved beyond rule-based tools to contain more complex mathematical models incorporating multiple static and dynamic factors rather than just the presence or absence of a variable. Despite the many advantages of CDS tools, widespread acceptance by clinicians across healthcare disciplines remains variable.

Computerized order entry (CPOE) and electronic health records (EHR) represent forms of computer assistance used in healthcare systems worldwide. CPOE and EHR centralize information and CDS can be incorporated into these technologies. CPOE and EHR with integrated CDS enables provision of abnormal lab value and allergy alerts, antibiotic choice assistance, vaccination reminders, mortality prediction tools, compliance with protocols and care guidelines, and suggestions for therapeutic interventions at the bedside[4,7,8]. The warehousing of information in EHR and other computer databases with CDS enables research advancement as databases can be linked and analysis of previously unrecognized relationships between patients and disease states explored[9].

Bedside computer monitoring devices can also be considered a form of CDS and have evolved from display tools to alarm systems and clinical assistance tools. For example, electrocardiography machines now provide a tracing as well as an interpretation. This type of analysis, using various inputs and known associations to generate a weighted output, is known as a neural network and is commonly utilized in both waveform analysis and mortality risk assessment tools[9]. Another type of CDS tool with increasing medical use is fuzzy logic; this permits use of ambiguous and imprecise data in logic control when constructing objective outputs. Applications include mechanical ventilation control, oxygen titration, and medication administration for blood pressure regulation[9]. Belief networks, another type of CDS tool, are algorithms derived from probability trees describing relationships of variables in a system to each other. Belief networks often utilize one of three models: simulation, mathematical, or statistical[10]. Belief networks can be designed to assist clinicians in real-time clinical decision making, and such belief networks have also been used to determine prognosis following head injury[9]. Effective computer decision support tools require high data integration accuracy and quality meshed with error free logic, ease of use, and explicit communication[11].

Experience with decision support and decision making in medicine

Current examples of accepted CDS tools include mortality prediction tools, such as the acute physiology and chronic health evaluation (APACHE) and pediatric risk of mortality (PRISM) scores. These have been validated and revalidated providing accurate mortality risk prediction and are routinely employed to generate risk adjusted mortality estimates to assess ICU performance[12,13]. CDS tools used in outpatient care document improved adherence to recommended vaccine schedules and adherence to recommended asthma care[14,15]. CPOE, with integrated CDS, decreases medical errors and improves pharmacy costs over time[16-20]. CDS tools have improved care in time-sensitive disease states including septic shock[21].

Table 1 Applications of computerized decision support in adult, pediatric and neonatal critical care

Type of support tool	Example or subject
Adult critical care	
Diagnostic	DXplain[28]
	Mortality and length of stay prediction[9,29]
Alert and reminder	Ventilator induced lung injury[84]
	Blood pressure variability while on vasopressors[32]
	Adverse drug reactions[19]
	Drug induced thrombocytopenia[30]
	Epidural hematoma with neuraxial anesthesia[31]
Protocol/procedure	Acute respiratory distress syndrome[33-35]
	Sepsis[21]
	VTE prophylaxis and events in trauma patients[37]
	VTE prophylaxis[38,39]
	Tidal volume during mechanical ventilation[36]
Management	Ventilator fraction of inspired oxygen[41]
	Pressure support ventilation[42]
	Antibiotic recommendation[43,44]
	Blood glucose control[46-48]
	Sepsis[21]
	Heparin dosing after myocardial infarction[45]
Research	Mortality prediction[29]
	Prediction of fluid requirement[53]
	Predictive alerts for hemodynamic instability[49-51]
	Ventilator settings[76]
	Prediction of dialysis need[52]
	Insulin e-protocol[54,85]
Pediatric and neonatal critical care	
Diagnostic	ISABEL (www.isabelhealthcare.com)[59,86]
	SimulConsult (www.simulconsult.com)[87]
	MEDITEL pediatric diagnostic system[58]
	Outcome prediction and severity of illness[55-57]
Alert and Reminder	Drug interaction[62]
	Prescription errors and adverse drug events[18,61]
	Parenteral nutrition orders[61]
	NICU pulse oximeter[60]
Protocol/Procedure	Blood transfusions[63]
	Medications[61]
	Parenteral nutrition[64]
Management	Oxygen in ventilated newborns[68]
	Antibiotic recommendation[44,65]
	Blood glucose control[69]
	Medication information databases[88]
	Medication dosing calculators[61]
	Ventilator management in neonates[66,67]
Research	Virtual PICU (www.picu.net)[89]
	Pediatric cardiac care consortium[70]
	Acuity scoring systems for quality improvement[56,57]
	Ventilator settings in neonates[71]
	Neonatal seizure detection[72]
	Glycemic control[90]

VTE: Venous thromboembolism; PICU: Pediatric intensive care unit; NICU: Neonatal intensive care unit.

Hunt *et al*[3] conducted a literature review on > 60 studies evaluating decision support tools to determine if these systems impacted patient care and found that CDS tools consistently enhanced performance for drug dosing and preventative care. Similarly, improvements in practitioner performance are noted in a review by Garg *et al*[22] with implementation of CDS systems.

Research on the effectiveness of CDS tools for more advanced clinical decisions in disciplines such as critical care are limited. Decisions rely heavily on clinical judgment and provider knowledge, and in the ICU environment, decisions are often affected by uncertainty. Clinical uncertainty among diagnoses and therapies makes conclusive decisions challenging[23]. Use of computer protocols or automated systems is still considered investigational; however, computers could assist clinicians' decisions by providing probabilistic estimates for diagnosis, choice of therapy, and survival[10]. Additionally, little is known about physician and nurse utilization or opinions of CDS tools[1]. To accurately assess the potential impact of a CDS tool by a clinical parameter, such as patient outcome, widespread tool use and acceptance is required[11]. Currently, use of CDS remains variable across different healthcare professionals and clinical situations[1,23,24]. Furthermore, an unappreciated challenge to CDS tools is that clinical decisions often incorporate patient and provider preferences. Some might term this phenomenon "the art of medicine." Therefore, it is not surprising that individual clinicians might resist incorporation of automated decision trees into their daily practice.

Despite advancements in the field, many pitfalls in both design and implementation of CDS tools occur and are multifactorial. In the review by Hunt *et al*[3] only 1 of 5 diagnostic aides showed a quantifiable benefit and in the review by Garg *et al*[22] only 4 of 10 diagnostic tools showed patient benefit. Diagnostic aides may be limited by variations within a diagnosis between patients and by the uncertainty of symptom variables collected from patients and inputted into systems. Also, measurement of meaningful outcomes in these studies is difficult when the intervention is designed to improve workflow and reduce barriers to guideline compliance. Other reports found no improvement or worsening in patient outcomes and costs after implementation of computerized systems[25-27]. Many reports have suggested that failure of some CDS systems is related to problems with implementation and not to content. Several studies highlighted learned lessons from failed implementation and suggested strategies for improved success. Seamless integration with existing systems and clinician workflow, limiting alarms in a system to prevent alert fatigue, and proper training before and after implementation are particularly important[1,7]. Additionally, the complex nature of human decision making adds confusion to measuring the effectiveness of CDS tools as many healthcare decisions are unstructured with high levels of uncertainty and depend on the judgment of the decision maker[1].

CURRENT APPLICATIONS OF CDS IN ADULT AND PEDIATRIC CRITICAL CARE

CDS systems in critical care continue to advance and are beginning to show improvements in care for both adult and pediatric ICU patients. A large amount of data is available for each ICU patient, and CDS tools are designed to assist the clinician in incorporating this multitude of data into patient specific therapeutic plans. Examples of CDS systems in adult critical care are provided in Table 1. Diagnostic support tools are available to assist in disease identification and also for using symptoms and patient condition on admission to predict outcome[9,28,29]. Ranson's criteria and various APACHE models are examples that have been validated using real time data to predict mortality risk in critically ill patients[29]. Alert support tools are used to improve workflow, warn practitioners of adverse drug reactions[19,30], and to notify practitioners of potential adverse consequences of an ordered therapy, such as anticoagulation[31,32]. This type of system decreases reported patient complications from drug-drug interactions and adverse drug events in the ICU following implementation[19]. In the prospective cohort study by Bertsche *et al*[19], implementation of a CDS program showed significant decreases in drug-drug interactions and in adverse events related to drug-drug interactions, including prolonged QT interval and hypokalemia. Additionally, CDS improves adherence to protocols for mechanical ventilation[33-36], sepsis[21], and venous thromboembolism prevention[37-39], and can improve patient care. Such protocol use in critical care standardizes treatments of common physiologic states and is often central to quality improvement efforts in the ICU[40]. Tafelski *et al*[21] demonstrated significantly increased adherence to standard care protocols for sepsis following implementation of CDS, and additionally reported a significant association between mortality and adherence to those care protocols. CDS is also used to aide patient management independent of protocols by recommending suggestions for ventilator settings and weaning[41,42], antibiotic assistance[43,44], and medication dosing. Mungall *et al*[45] found significant improvement in achieving desired anticoagulation goals when using a CDS tool for heparin dosing following tissue plasminogen activator treatment in myocardial infarction compared to the standard nomogram. Blood glucose control is a commonly investigated area for support tools, and studies report more consistent target glucose levels and few adverse events with these tools[46-48]. CDS is also used for research in improving mortality risk estimation[29], prediction of hemodynamic instability[49-51], and in forecasting the need for therapies in the ICU, such as dialysis[52,53]. CDS tools can also reduce variability of clinical decisions during critical care research, therefore enabling replicable experimental methods and reproducible results[54].

Pediatric and neonatal ICUs are also utilizing CDS tools with increasing frequency, and specific examples are provided in Table 1. Multiple support tools are available to aide in diagnosis, classification of disease severity, and outcome prediction[55-59]. ISABEL is one such diagnostic aide that is commercially available as a standalone product or for integration into existing EHR systems and has shown good sensitivity for common pediatric diagnoses[59]. PRISM models and score for acute neonatal physiology (SNAP) models are validated tools for mortality risk prediction in pediatric and neonatal patients[55,56]. CDS alerts improve patient safety and are used to warn of drug interactions and adverse events and to improve the specificity of monitor alarms[18,60-62]. Kadmon *et al*[18] found alert CDS tools integrated with CPOE significantly decreased dosing order errors and potential adverse events in a pediatric ICU. Similarly, use of these tools reduced parenteral nutrition order errors in the neonatal ICU[61]. Similar to adult tools, CDS in pediatrics provides improved adherence to care protocols for blood transfusion, parenteral nutrition, and medication orders[61,63,64]. Adams *et al*[63] found a significant reduction in pediatric blood transfusions, consistent with best practice guidelines, when CDS was added to CPOE. Pediatric CDS tools also assist patient care by providing antibiotic assistance[65], medication dosing calculators[61], and ventilator management suggestions[66-68]. These management tools have improved attainment of target oxygen saturations in newborns and target blood glucose concentrations in critically ill children[68,69]. CDS tools are also used for pediatric and neonatal research on a variety of topics, including seizure detection and quality improvement[56,57,70-72].

BARRIERS TO WIDESPREAD ACCEPTANCE OF CDS IN THE ICU

CDS tools are not uniformly incorporated into critical care units. There are many barriers to widespread acceptance, including style of implementation, variability in provider preference, and perceived lack of generalizability to patient populations. Use of CDS tools is largely optional and determined by either provider preference or group consensus and a cultural shift must occur to ensure broad utilization[11]. Additionally, the formation of CDS tools through integration of independent systems, such as EHR, with probability estimates from different ICUs is complex and dependent on the quality and generalizability of the data collected[29]. Likewise, data used to create a protocol often rely on imperfect data, such as from meta-analyses, that individual clinicians may determine are not generalizable to their patients[73,74].

Even the use of simple computer protocols for care items like ventilator weaning can ignite objection from clinicians who value the importance of individual patient specific decision making. Some argue CDS tools overly standardize medicine and fail to satisfy the complex nature of ICU decision making. Proponents cite the unique processing capabilities of computer networks and the advantages of analyzing several data points simultaneously[29]. CDS tools also allow for programming models that can respond to patient specific states and data[54]. CDS tools are meant to support, not replace, clinical decisions and can expand limited human recall by presenting several data points simultaneously. The successful use of CDS tools in the ICU relies heavily on the preferences of clinicians and on the specific contexts and degree of uncertainty present for a given clinical decision[1].

Additionally, some failures with CDS tools have been noted in the literature. Han *et al*[27] reported an unexpected increase in mortality associated with implementation of a CPOE program with integrated CDS due to delays in medication ordering, dispensing, and administration to critically ill patients. These delays were linked to unanticipated delays in workflow with early implementation. The published failures highlight the importance of proper design, implementation, and deployment of CDS tools. Mitigation of changes to clinician workflow and widespread user acceptance are important to production of a successful CDS tool.

POTENTIAL FOR CDS IN CRITICAL CARE

Advancements in computer technology and mathematics have already led to improved technology for aides in critical care, but have the potential to enhance clinician performance and patient care even more. Bedside monitors collect vast amounts of information that are currently analyzed at discrete time periods by clinicians. Neural networks and fuzzy logic systems are two types of tools that can be integrated into these bedside alarms to provide continuous analysis and potentially identify patterns consistent with various diagnoses, such as cardiac ischemia and hypovolemia[9]. Evaluation of hemodynamic data for prediction of instability and hypotension is an ongoing area of research that could translate into bedside tools in the future[49-51].

Continuous electroencephalogram (EEG) is a commonly used critical care tool from which patients and clinicians may benefit from rapid identification of seizures or prediction of seizures before they occur. Retrospective evaluation of EEG data by various mathematical techniques has shown good detection of seizure and identification of pre-ictal states minutes to hours prior to onset of seizure activity; no prospectively evaluated models have proven effective, though new methods are being researched[75]. Fuzzy logic controllers could also be used with bedside devices to provide automatic adjustment of ventilators or dialysis machines by integration of patient specific information and programmed logic controllers[9].

CDS for mechanical ventilation in adults and children has already shown good agreement with clinician recommendations[71,76,77]. In the future, these CDS tools could provide independent control of ventilator settings based on patient specific data. CDS tools also have the potential to manage decisions regarding titration of medications or weaning of support devices, thereby freeing the clinician's mind to direct the overall care of a patient. CDS incorporated into CPOE could also be used to decrease unnecessary testing or to enhance the proper selection of available tests, such as radiologic exams, based on patient information[78]. Incorporation of belief networks and neural networks into existing EHR could also provide tools for identifying diseases or estimating the probability a patient will develop a disease, such as sepsis or acute respiratory distress syndrome[9]. As septic shock is a disease with time-sensitive implications for outcome, use of prediction tools could alert clinicians to high risk patients that may benefit from additional or different therapies[79]. Additionally, the adoption of CDS linked into EHR systems could identify patients presenting to small facilities with time-sensitive diagnoses and disseminate ICU protocols to providers lacking in-house critical care specialists.

In addition to identification of disease for clinical support, CDS tools integrated into existing EHR or databases can rapidly identify patients for inclusion into research studies[80]. Utilization of CDS in this way has the potential to increase recruitment numbers, especially among studies with time dependent inclusion criteria. CDS can also provide automatic data capture for research studies by tracking patient information and automatically transmitting it to a central data coordination center, saving coordinator time and potentially costs[11]. This automatic capture can also be used to operate research protocols, potentially improving compliance[11]. CDS can standardize co-intervention control during multicenter prospective clinical trials. Co-interventional control improves the signal to noise ratio on pertinent clinical questions, thereby standardizing clinical experimental methods and enhancing the probability of accurate trial results[81,82]. Finally, increased use of CDS with EHR and data warehousing provides opportunities for collecting information across many institutions. This data provides cohorts for research on rare diseases or chronic diseases that could close existing gaps in medical evidence and improve care for patients[83].

CONCLUSION

Computerized decision support systems are becoming increasingly common in medicine, though barriers to widespread acceptance continue to exist. Studies have shown benefits to their use in a variety of applications, but research regarding improvement in patient outcome is limited. Studies have also shown that careful and proper implementation is crucial to the success of these systems. Critical care physicians are in unique environments where the use of CDS could play a significant role in patient safety and outcome over the coming years. CDS has the potential to provide improved care standardization, faster diagnosis and treatment, reduced medical errors, improved health care costs, and unique research opportunities that could all translate into improved patient outcomes over time. Advancements are occurring in the field of CDS and promise to improve current technologies and to yield exciting new technologies for clinicians in the future.

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