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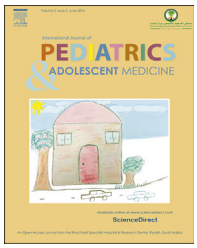

ORIGINAL RESEARCH ARTICLE

Data visualization for truth maintenance in clinical decision support systems

Gilbert Chien Liu [a,*], Jere D. Odell [b], Elizabeth C. Whipple [c], Rick Ralston [b], Aaron E. Carroll [c], Stephen M. Downs [d]

[a] Department of Pediatrics, University of Louisville, Louisville, KY, USA
[b] Ruth Lilly Medical Library, Indiana University School of Medicine, Indianapolis, IN, USA
[c] Department of Pediatrics, Indiana University School of Medicine, Indianapolis, IN, USA
[d] Children's Health Services Research, Indiana University School of Medicine, Indianapolis, IN, USA

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Abstract *Background and objectives:* The goal is to inform proactive initiatives to expand the knowledge base of clinical decision support systems.
Design and setting: We describe an initiative in which research informationists and health services researchers employ visualization tools to map logic models for clinical decision support within an electronic health record.
Materials and methods: We mapped relationships using software for social network analysis: NodeXL and CMAP. We defined relationships by shared observations, such as two Arden rules within medical logic modules that consider the same clinical observation, or by the presence of common keywords that were used to label rules according to standardized vocabularies.
Results: We studied the Child Health Improvement through Computer Automation (CHICA) system, an electronic medical record that contains 170 unique variables representing discrete clinical observations. These variables were used in 300 medical logic modules (MLM's) that prompted health care providers to deliver preventive counseling or otherwise served as clinical decision support. Using data visualization tools, we generated maps that illustrate connections, or lack thereof, between clinical topics within CHICA's MLMs.
Conclusions: The development of such maps may allow multiple disciplines commonly interacting over EMR platforms, and various perspectives (clinicians, programmers, informationists) to work more effectively as teams to refine the EMR by programming logic routines to address co-morbidities or other instances where domains of medical knowledge should be connected.
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* Corresponding author. Tel.: +1 (502) 852 3737; fax: +1 (502) 852 2203.
E-mail address: gil.liu@louisville.edu (G.C. Liu).
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1. Introduction

The purpose of clinical decision support (CDS) is to provide information that improves health care decision-making. Examples of CDS tools include order sets created for particular conditions or types of patients; databases that can provide information relevant to particular patients; reminders for preventive care, and alerts about potentially dangerous situations. CDS can potentially lower costs, improve efficiency, and reduce patient inconvenience.

The refining of knowledge bases within clinical decision support represents a challenge of 'truth maintenance' [1]. Those developing the logic foundations of decision support programs for health care applications must construct computational models of clinical situations. To keep these models consistent with new knowledge, the reasoning programs frequently need to remove or update portions of their models. Truth maintenance involves determining the current set of beliefs from the current set of reasons, and updating the current set of beliefs in accord with new reasons in a typically incremental fashion.

We describe a truth management initiative that employs visualization tools to map computational models within an electronic medical record (EMR), the Child Health Improvement through Computer Automation (CHICA) system. The goal for mapping CHICA's computational models is to inform proactive initiatives to expand the knowledge base of CHICA's decision support system. The maps define geographies in which there are topic "continents" that indicate well connected clinical domains versus topic "islands and oceans." Knowledge islands may indicate scenarios where there is an absence of related content to support coordinated delivery of clinical services that should connected. An example of such connected services is how clinicians approach the diagnosis of obesity, the possibility of associated metabolic disorders (e.g. dyslipidemia, hypertension, insulin resistance), and the need to explore relevant health behaviors (e.g. exercise, diet). The development of such maps may allow multiple disciplines commonly interacting over EMR platforms, and various perspectives (clinicians, programmers, informationists) to work more effectively as teams to refine the EMR [2].

2. Materials and methods

CHICA is a decision-support and electronic medical record system for pediatric health maintenance and disease management [3–6]. The HL7 International (www.hl7.org) Arden Syntax for Medical Logic Modules (MLMs) is an ANSI-approved American National Standard language for encoding medical knowledge and representing and sharing that knowledge among personnel, information systems and institutions. CHICA uses a library of Arden Syntax rules that utilize existing patient clinical data to deploy patient screening instruments, as well as prompt health professionals to deliver specific aspects of care. CHICA also uses a global prioritization scheme to determine which information is most relevant for inclusion on forms printed for patients or health care providers. These various systems effectively constrain the number of topics that CHICA recommends to be addressed a feasible number for any given patient encounter.

In CHICA's Arden rules based syntax, there are stored observations contained in medical logic modules (MLMs). We assigned Medical Subject Headings (MeSH: http://www.ncbi.nlm.nih.gov/mesh) terms and Unified Medical Language System (UMLS: http://www.nlm.nih.gov/research/umls/) terms to 450 MLMs, taking into account the hierarchical nature of stored observations. We then created pivot tables that contained all categories of stored observations to analyze how observations were shared by MLMs.

We mapped relationships within CHICA's knowledge base using software for social network analysis: NodeXL by Cody Dunne and Ben Schneiderman at the University of Maryland (for more information, please see http://nodexl.codeplex.com) and CMAP (Florida Institute for Human & Machine Cognition, Pensacola, FL). Both knowledge visualization tools have multiple options for laying out diagrams — options were selected and chosen to optimize ease of visualization, incorporating factors such as readability and recognizability. We defined relationships by shared observations, such as two Arden rules that consider the same clinical observation, or by the presence of common keywords that were used to label rules according to standardized vocabularies.

3. Results

At the time of the mapping process, three hundred MLMs were actively storing observations in CHICA, and as a result, there were 170 unique variables. MLMs generate a range of one to five variables. The median number of variables per MLM is one, and the average number of variables per MLM is 1.5 (see Table 1). The number of MLMs referencing any single variable ranged from one MLM to a maximum of twenty MLMs. The median number of MLMs that referred to a specific variable was two, and the average number was 2.8 (see Table 2).

Using data visualization tools, we generated maps that indicate the geography of CHICA's MLMs consists primarily of islands. For example, evidence strongly supports grouping body mass index (BMI) screening, cholesterol screening, blood pressure evaluation, and counseling about

Table 1 Distribution of Medical Logic Module (MLMs) counts by number of stored observations within a single module.

Number of stored observations per MLM	Count of MLMs
5	5
4	13
3	17
2	76
1	189
	Total MLMs = 300

Table 2 Distribution of times variables were present in different Medical Logic Modules (MLMs).

Number of MLMs sharing variables	Number of variables
20	1
13	2
11	1
10	5
9	1
8	3
7	3
6	3
5	4
4	11
3	25
2	40
1	71
	Total Variables = 170

breastfeeding as topics to be jointly considered when delivering pediatric preventive services to prevent obesity and associated co-morbidities. The US Preventive Services Task Force rates BMI screening and breastfeeding counseling with a grade of "B," indicating that the literature can be interpreted with high certainty that the net benefit is moderate or there is moderate certainty that the net benefit is moderate to substantial. Multiple U.S. and international health organizations have issued guidelines that direct health care providers to assess cholesterol or other lipid levels, as well as blood pressure when managing overweight or obesity in children [7]. The maps of the MLMs related to these topics are presented in Fig. 1 "Obesity islands and ocean," and illustrate the lack of shared observations that would connect the MLMs, and thus deliver decision support that could coordinate physician actions to address related topics.

The addition of controlled vocabulary terms increased linkages between MLMs, transforming the geography of the knowledge map to lessen the presence of "islands." In certain instances, "continents" of linked clinical topics represent a more desirable circumstance in which computational models can more effectively support clinicians as they approach health risk factors, determine likelihood of disease, and develop a plan for diagnosis and treatment. CHICA contains MLMs that identify risk factors for child abuse based on responses from a patient's parent to a written survey (the Prescreener Form — PSF) that is self-administered and often completed in the waiting room prior to being evaluated by a health care provider. Fig. 2, "Map of MLM's regarding child abuse," depicts medical logic modules regarding the patient's parent report of experiencing domestic violence, which is considered a risk factor for child abuse, and linked to decision support processes that prompt physicians to explicitly investigate and document that they have addressed the information from the Prescreener Form. Fig. 2 also depicts a MLM of a patient's parent report of experiencing depressive symptoms, also considered a risk factor for child abuse. Parent depressive symptoms are not linked by virtue of shared variables with child abuse MLMs. The addition of MeSH and UMLS terms to MLMs combined with data visualization of relationships between MLMs identified links that could increase the effectiveness of the decision support system to prevent child abuse.

4. Discussion

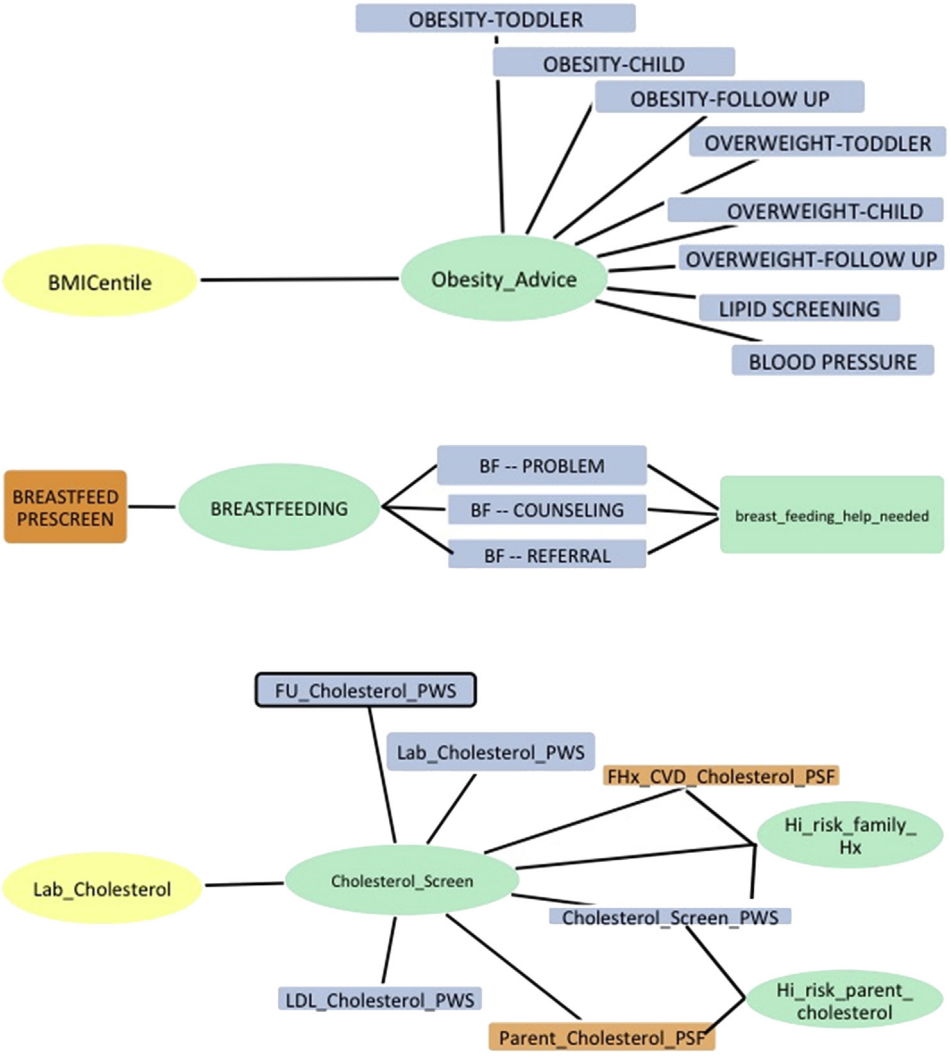
Knowledge acquisition and knowledge modeling play an important role in the successful implementation of clinical decision support systems [8]. Traditional approaches to identifying and describing structures of bodies of knowledge include standard vocabularies, taxonomies, and ontologies [9—11].

While textual organization may be a common way to map knowledge, the increase in visualization of information [12,13] is on the rise and can allow for a more rapid interpretation of information. Bibliometric analysis has been used to analyze knowledge domains [14] as well as create knowledge maps based on analyses that detect when articles are cited together in references of subsequent publications [15]. A knowledge map is one way to accurately capture and display disparate pieces of information, visualizing the connections between complex silos of information [16]. A visual map can enhance the information and display connections that hitherto were undiscoverable (or at least very difficult to grasp).

By using open access software for data visualization, we were able to display linkages between medical logic modules, showing relative amounts of linkages based on shared stored observations. We also were able to identify opportunities to create additional linkages that addressed potential deficiencies in clinical decision support. The mapping process can support truth maintenance, but it would rely on verifying that missing linkages indeed represent clinical scenarios wherein topics should be jointly addressed. In such instances, informationists need to work with clinicians to implement strategies to use this information to modify electronic health records with clinical decision support systems such as authoring new rules or adding common observation terms to join MLMs.

The data visualization tools that we used have options for manipulating generated maps to optimize readability and recognizabiltiy. Other dimensions of map views can be manipulated based on *a priori* categorization of health data such as contextual factors. For example, when health care providers aim to modify a patient's health behavior, socio-ecological theories may guide medical decision making by structuring investigation based on a pediatric patient in the context of family, living in neighborhoods, or being affected by social environment factors such as difficulty accessing health care. Also, data could be considered by the source, such as whether information is arriving from laboratory testing, nursing assessment, or physician examination.

Clinical decision support systems have shown great promise for reducing medical errors and improving patient care. As the use of electronic patient data and clinical knowledge sources increase, truth maintenance strategies are needed to optimize accurate transfer of such information to health care providers, in formats that are selective and task specific. Continuous improvement of electronic



Abbreviations: PWS: Provider work sheet; FU: follow up;
CVD: cardiovascular disease; PSF: prescreener form

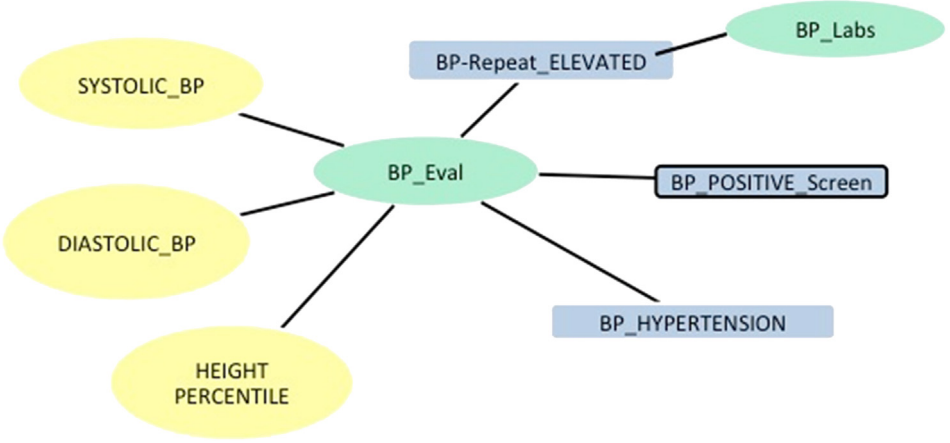


Figure 1 Obesity islands & ocean.

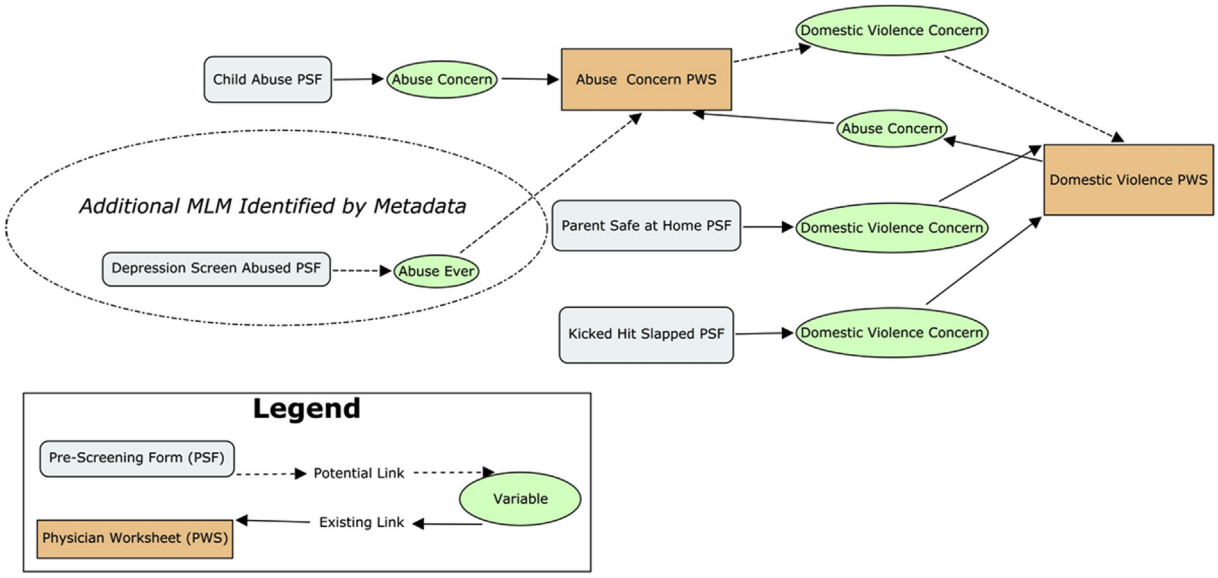


Figure 2 Map of MLM's regarding child abuse.

health records (EHR) is a primary approach to achieving societal and institutional imperatives of reduced practice variation and more appropriate resource utilization. Equally important is that EHRs directly benefit individual clinician decision makers and their patients; clinical decision support should allow physicians to focus their expertise on synthesizing available clinical knowledge and patient data rather than wasting precious time and effort on simple information-retrieval tasks, and patients will benefit from higher quality decisions as a result.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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