**ABSTRACT**

The development and implementation of competent and cost-effective computerized medical records that profoundly improve physician productivity and knowledge management will require the development of a new paradigm for the representation and analysis of medical knowledge and logic. Medical knowledge is acquired inductively by observing, measuring, and eliciting information from patients in a process that is investigational rather than transactional. Most, if not all, current approaches to health information technology (HIT) rely on a logic and data structure that imposes significant limitations on the ability of physicians to thoroughly and efficiently document and access empiric patient data because the information is almost invariably organized in a way which presumes, rather than makes explicit, the relationships of concepts and their meaning. Cmapping provides a graphical method of capturing and displaying expert content knowledge that is simple to comprehend and modify and provides a foundation for a dynamic, inductive, and inclusive method of clinical documentation and research. The basis of medical decision analysis along with representative samples of medical knowledge modeling in the Cmap format is presented. The knowledge structures that are captured in Cmaps can be expressed directly in propositional logic, enabling the capability to convert Cmapped clinical expressions to be used to define a description logic for clinical evidence documentation and analysis that can in turn be mapped to multiple natural languages. The described description logic approach can be used to formulate digital messages and documents and to automate the process of converting description specifications formulated in propositional logic into operational electronic health record solutions for capture and reporting of clinical encounters. It has also been demonstrated that using Cmaps to elicit content knowledge from physicians to build point-of-care clinical documentation screens can significantly reduce the time and costs necessary to implement the physician’s knowledge into operational systems and that using Cmaps eliminates the need for HIT expertise in the rules-encoding process.

**SINOPSIS**

Para elaborar y aplicar historias clínicas informatizadas competentes y rentables, que mejoren notablemente la productividad de los médicos y la gestión de la información, es necesario crear un nuevo paradigma para la representación y el análisis del conocimiento médico y la lógica. El conocimiento médico se adquiere de forma inductiva, mediante la observación, la predicción y la recogida de información de los pacientes en un proceso que es más experimental que transaccional. La mayoría de las estrategias actuales de las tecnologías de la información sanitaria (TIS), si no todas, dependen de una estructura lógica y de datos que limita de manera considerable la capacidad de los médicos a la hora de documentar y acceder de forma eficiente y exhaustiva a los datos empíricos de los pacientes, ya que la información está casi siempre organizada de modo tal que supone, en lugar de hacer explícitas, las relaciones entre los conceptos y su significado. La utilización de mapas conceptuales proporciona un método gráfico de captura y presentación de informe.
The basic science and clinical foundations of modern medicine are evolving so rapidly and broadly that the advantageous and efficient capture, access, and use of this vast amount of data have generated a worldwide challenge to effectively use modern health information technology (HIT) to improve the health of the world’s citizens. The US government recently embarked on an unprecedented program to convert the current US medical health records system into a universal, interoperable, clinically meaningful electronic system by 2015. This has been mandated in the context of the extremely rapid and virtually universal adoption of computerized practice management systems in the United States in the past 2 decades. A recent estimate for the adoption rate of electronic medical records (EMRs) for single-doctor offices is between 30% and 37%, while the estimate of the adoption rate for offices with 6 to 10 doctors is between 63% and 65%.1

It has commonly been assumed that such systems (1) would be developed as elaborations of currently existing clinical computer technology; (2) could be modeled on current specialized systems, such as radiology and emergency medicine HIT, for other specialties, such as ophthalmology and dermatology; and, (3) that there would be significant improvements in safety, quality, and efficiency that would rapidly lead to lower healthcare costs. These assumptions have not been scientifically demonstrated and may not be valid, and the failure to take these possibilities into consideration may lead to qualitative and fiscal degradation of healthcare. Despite the obvious incentives and the example of successful implementation in several specialties, there has been widespread reluctance and uncertainty about the general adoption of such systems by most medical practitioners, if not by administrators, politicians, public advocates, and others.

Physicians have widely adopted costly and complex new diagnostic and therapeutic instruments. They have been willing to undertake extensive continuing medical education to learn newer and better techniques of patient care. Most physicians will use tools that they find are consistent with or can be adapted to their personal approach to patient care and practice management. It is our premise that the structure of current HIT is inconsistent with the core of clinical medicine and that this inconsistency has motivated the inertia that has resulted in slow and limited adoption of HIT for clinical documentation.

One of the commonly accepted approaches to conceptualizing the information access and use in a clinical encounter has the acronym SOAP, which describes a process of subjective evidence collection, objective evidence collection, evidence assessment and diagnostic and intervention treatment plan. For example, an encounter may consider such evidence at a single point in time or over a period of time and may look at trends, clusters, and other data relationships. Generally, a clinician will use evidence and the assessment process to hypothesize a diagnosis to explain the evidence and to provide an organizing principle on which to base planning. This information use process has been described as medical reasoning.2

The evidence collection process is iterative and continues as new information is discovered or acquired. The collection continues until sufficient information has been acquired to confirm a diagnosis and/or disconfirm alternative diagnoses and complete the planning process appropriate to the current encounter. Evidence collection may continuously change the prognosis and planning process.

Paper notes have traditionally been idiosyncratic and quite personal because their purpose was to assist in recalling details of a patient encounter or to act as a reminder for a subsequent patient encounter. A substantial portion of the content has been implicit and contextual, and many clinicians have developed personal shorthand systems to streamline record keeping. Relevance judgments during encounters have affected the quantity and quality of information recorded.

A paper note can easily be scanned and converted into a digitized medical record, but such scanned documents require a human to read and interpret the clinical notes. Dictation and transcription can similarly be used to create a digitized medical record. In both cases,
it is common to have professional coders evaluate medical records and mark up encounters with the diagnosis and procedure codes required by payers. Metadata annotation and some structured information capture can contribute to retrieval and machine billing, but such record systems are not particularly semantically interoperable, and they do not enable the computer to be leveraged to improve clinician productivity.

**FORMALIZING THE WAY CLINICAL INFORMATION IS RECORDED AND COMMUNICATED**

Fundamental to semantic interoperability between and among users is a common language, format, and method for documenting encounters so that they can be easily read and used by other clinicians. Using natural language as a model, clinicians must agree upon a vocabulary, syntax, and grammar for constructing well-formed clinical statements and defining organizing principles that can be used to structure, sequence, and extract relevant portions of clinical documents. Though there are many initiatives actively seeking to develop such standards and many vendors that have developed structured information templates, the match between user needs and available off-the-shelf solutions has not been sufficient to motivate widespread adoption by clinicians.

In many cases, clinicians need to specify their own requirements to meet the unique needs of their clinical practices. This specification process has traditionally required engineers to develop requirement specifications that are used to develop operational software or to modify vendor templates. This approach presents both economic and quality challenges. The intermediation process in which a knowledge engineer works with a clinical content expert to specify requirements is cumbersome and can be prone to error. The knowledge requirements of clinical specialties prompt clinical specialists to define their terms and to specify how they organize knowledge to document relevant information that can be used to communicate observations, measurements, signs, symptoms, diagnoses, prognoses, and plans.

Accessibility and legibility seem to be the principal values sought from digitized medical records. Accessibility can be achieved with scanned charts even if those charts are not universally legible. Legibility can be achieved in a variety of ways, including dictation and transcription; however, to achieve communication of information between and among users requires that the information have the same meaning to each user. The ability to contribute to user productivity by summarizing or processing information to enable statistical analysis, quality reporting, translational research, etc, requires semantic interoperability and organization and representation of information that facilitate automated computation.

The development of detailed clinical models is in its infancy. The meaningful use requirements of the US Department of Health and Human Services (HHS) are limited to the complexity typical of recording vital signs and calculating body-mass indices. In some clinical situations, an observation that includes a finding and finding site may be sufficient, but if the finding involves contingent components, the rules for formulating a complete and correct clinical statement can become complex.

To pragmatically involve clinicians in developing useful, detailed clinical models to use in recording and communicating clinical-encounter information requires functionality to convert the models and implement the modeling results directly into an EMR system that can be used for clinical-encounter record keeping. The modeling and development of a specialty vocabulary, such as the American Academy of Ophthalmology SNOMED-CT subset, without a mechanism to directly implement and use it in a functional EMR, limits that model’s pragmatic usefulness to the annotation of documents, such as the basic science course for ophthalmology residents.

We have experimented with concept mapping (Cmapping) and have concluded that it is a useful tool for the capture of expert knowledge in a way that lays the foundation for further advances in the development of information technology (IT) that will improve the access, quality, and safety of medical care.1-5 We believe that such systems should enhance physician and other provider productivity and effectiveness and consequently lower costs. Such a system should also provide a foundation for new approaches to research of large and diverse populations across cultural and linguistic boundaries. In addition, the system could also encourage better patient counseling. Patients can use many of the Cmaps to better understand their conditions and treatments. The theory of knowledge and the theory of learning that underlie the concept-mapping tool views concepts as the primary units of knowledge and defines a concept as “a perceived regularity or pattern in events or objects, or records of events or objects designated by a label, usually a word(s).”6 Concepts alone convey little meaning, and the basic unit of meaning in concept maps are propositions, ie, a concept linked to another concept with an appropriate “linking word” or words.6,7 Additionally, concept maps are usually organized hierarchically with the most inclusive concept and propositions at the top and progressively more specific, less inclusive concepts lower in the map. This organization is also congruent with the ways our brains store information. The relative simplicity of concept map structure nevertheless conveys the meanings we seek to preserve and transfer with precision. The number of propositions shown in a concept map is indicative of the number of meanings or ideas conveyed by that map.

To overcome the limitations of current software design and development, a predominately automated process is required to translate detailed clinical models into useful EMR templates. We propose the use of Cmaps for the specification of detailed clinical models of specialty and subspecialty medical knowledge and, working with MedTrak Systems, Inc (www.medtrak-
systems.com), have developed and demonstrated a conversion process that enables the Cmaps to be predominately automatically used to drive a production EMR system.

CLINICAL DATA STRUCTURE AND LOGIC

Cmaps are particularly useful for content experts to collaboratively describe clinical findings to essentially any level of detail. It is possible to annotate concepts with textual and image-based references. It is important in clinical documentation systems based on a detailed clinical knowledge model not to blend empiric evidence with inference or diagnosis, but to express evidence and inferences using a common terminology that is semantically consistent. Physicians may wish to describe the physical findings, capture patient history, and make measurements with instruments that are properly calibrated or standardized. Each observation, measurement, sign, or symptom must be captured and described at whatever level of specificity is known or relevant. Evidence must be able to be represented at the desired level of detail.

Blood pressure measurement seems to be a simple piece of data to capture. In most situations, the patient’s identifying information is connected to the diastolic and systolic measurements, as illustrated in Figure 1.

![Figure 1 Simple blood pressure description model.](image1)

There are times that such a representation of blood pressure is incomplete and insufficient, particularly in critical clinical situations, such as in intensive care or surgery. Although not exhaustive, Figure 2 illustrates a greater level of complexity that may be required to document a not-so-simple blood pressure.

In the context of a paper record, one would record the particular details that modify and contextualize the finding. In an EMR, however, the functionality to capture that detail must pre-exist, or the data may be recorded without the requisite modifiers.

Clinical findings may require reinterpretation over months to years by the same or new providers. Descriptive functions historically have tended to be idiosyncratic and personal because they represented notes intended to jog memory at a future time. These

![Figure 2 Complex blood pressure description model.](image2)
personalized documentation systems may not be easily interpreted by others. It is often unfamiliarity with the descriptive meaning that prevents rapid interpretation of older or unfamiliar records rather than the infamous “bad handwriting” of doctors. The major barrier to understanding the implications or meaning of a predecessor’s clinical note is much less the decryption of the words themselves—the lexical content—but rather the difficulty is interpreting accurately the clinical intent or the semantics of the record.

The traditional medical decision cycle is a specific example of a general decision cycle description as formulated by Boyd in the 1960s and 1970s. The cycle is known as the Boyd Cycle or Observation-Orientation-Decision-Action (OODA) Loop (Figure 3). The relevance of Boyd’s OODA cycle to medicine is easier to understand when applied to every aspect of medical decision-making—from the slow-motion management of neurodegenerative disease to intraocular microsurgery. Cycle time can be a critical element in medical outcomes, particularly if physician decision-making lags behind the disease process or anatomical complexity of the surgical field.

The fundamental requirement of any clinical documentation system, written or electronic, is preservation for subsequent use of information that informs the evolution of the clinical decision cycle. This cycle is characterized by a process of examination, diagnosis, prognosis, and treatment (Figure 4). Examination is composed of the collection of empiric data in a process that is affected by cultural, environmental, scientific, and other factors. Then, considering such elements as the training and experience of the physician, the availability of particular diagnostic modalities, etc, a diagnosis is arrived at, which is a provisional explanation of the empiric findings. A prognosis is the element of the medical decision cycle that represents the clinician’s expectations for the ongoing health state of the patient. Temporal, symptomatic, physiologic, etc, hypotheses may be articulated at this time. Therapy is the action that may be taken to intervene in the progress of the patient’s condition. The cycle continuously repeats until some conclusive endpoint is reached.

The Boyd Cycle, which was first developed to describe the interactions of fighter pilots in aerial combat in the Korean War, is clearly instructive in showing the importance both of making the right decision and making it in the right timeframe in the physician’s fight for the patient’s well-being (Figure 5).

The other critical use of clinical documentation is to facilitate learning and discovery to improve the understanding and treatment of disease. The earliest uses of such documentation go back to the earliest written records of ancient civilizations where written

![Figure 3 Observation-Orientation-Decision-Action Loop.](image-url)
CMAPS IN THE DESCRIPTION OF CLINICAL INFORMATION STRUCTURE AND LOGIC

Feature

Figure 4 Medical decision cycle.

and oral transmission of medical knowledge was used. The formal case study and the earliest epidemiologic research relied on careful observation and documentation that were supported by the evolution of the scientific method that began in the late Renaissance. Research of this type has continued to this day, with many modifications and refinements of design, interpretation, and mathematical analysis. The double-blind controlled clinical trial has been the gold standard of research for almost 50 years, with many successes to its credit. These studies have become increasingly complex, costly, and, in many cases, have outcomes where the difference between the successful and the unsuccessful may be statistically, but not particularly clinically, significant. There may be so many years between the beginning of these studies and their availability for evaluation, discussion, and incorporation into clinical practice that they may become obsolete by the time they are finished.

The fundamental element of any clinical trial is the study protocol. A protocol standardizes not just the words of a study, such as a description of pain, but standardizes the meaning of the words (ie, the semantics). This allows for the combination of standardized elements in order to perform comparisons and contrasts among populations. Standardization also brings the ability to extract, or factor, recurring or unique elements in the study population. The challenge of 21st-

Figure 5 Observation-Orientation-Decision-Action Loop—medical decision cycle.
century medical science is to develop the tools that are necessary to deal with the superficial, or phenotypic, human heterogeneity in the context of explosive discoveries in the underlying standardization, or genetics, of the human species.

The True Electronic Research Library (True ERL) initiative of the Washington National Eye Center has begun the development of tools to capture the detailed empiric descriptive knowledge that is necessary to completely, correctly, and continuously model one specialty area of clinical medicine, ophthalmology. We have been developing Cmaps with high complexities that capture clinical concepts that can be observed, measured, or elicited. Examples of such Cmaps are clinical descriptive models of the iris (Figure 6) and of the macula lutea of the retina (Figure 7).

The highlighted propositional chain in Figure 6 may be considered as the foundation of a discrete, complete, and unique clinical statement. This clinical statement can be extracted as a linear Cmap (Figure 8) to clarify how this approach can be used to capture and store empiric data in a new and revolutionary way.

Figure 8 may be interpreted, in English, as

_The right (OD) iris has a finding, which is an aperture which did not involve removal of iris tissue (which would be an iridotomy) by surgical means and which iridotomy is through-and-through the iris._

The Cmap of macular observations (Figure 7) with the linked sub-Cmaps (Figures 9 and 10) is a highly complex representation of what a comprehensive ophthalmologist may wish to describe on a clinical examination. It is almost certainly incomplete from the perspective of a retinal specialist. It is the

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**Figure 6 Iris description model.**
CMAPS IN THE DESCRIPTION OF CLINICAL INFORMATION STRUCTURE AND LOGIC

The power of the Cmap graphical and logical structure that easily permits additions and alterations in a knowledge model. CmapTools provide the option of creating concept maps that can have icons attached to a concept that can access any digital resource including submaps, URLs, images, etc. These maps are referred to as knowledge models, and all files attached to the root map are transferred when the latter is moved to another server or file. Such knowledge models may, in turn, be used to construct a clinically useful EMR.

We intend to continue to elaborate these representations with the help of our specialty and subspecialty colleagues. MedTrak Systems, an EMR and practice management systems developer and vendor, in collaboration with the True ERL, has developed software that can automatically convert Cmaps into EMR templates.

Figure 7 Macula lutea description model.

Figure 8 Iris clinical statement.
Figure 9 Vessels retina linked Cmap from Figure 7.
checklists, etc. We believe that the tools and processes that the True ERL is developing for ophthalmology can be used to model the rest of medical knowledge. It is the purpose of this article to introduce the use of concept mapping as a powerful tool in the continuous development and management of 21st-century medical knowledge.

**SEMANTICS**

Terms may have implicit meanings that are supplied by a reader when the reader encounters those terms. To communicate meaning in a way that is consistent and persistent, terms must be explicitly defined by an author and used by the author in a way that can be determined by any reader. An explicit meaning is used to convey the semantic intentions of the author as expressed by that author in a published definition either authored or adopted by the writer. Without traceable connections between concepts and their definitions, meaning cannot be consistently or persistently communicated and interpreted.

The first step in converting a Cmap into a semantically interoperable system of description is the capture and publishing of explicit meanings for terms and the construction of a symbol set that can be used to substitute for natural language phrases that users interpret implicitly. Descriptive conceptual terms or names in the Cmaps are then replaced with a universally unique semantic identifier (uuSID) that is used to link the concept to the definition supplied or adopted by the author. Table 1 contains the lexical form of the concept (concept name) from the Cmap, a definition, and a uuSID symbol that is used to represent the definition.

**STATEMENT FORMULATION**

Once concepts have been defined and a uuSID has been assigned, the Cmap may be converted into a descriptive form that shows the relationships between and among uuSIDs (Figure 11). This form is not user readable or user friendly, and so it would not be used in a human-computer interface; however, it would be used as an internal system map to describe the permissible propositional chains that have meaning with respect to the scope described by the Cmap’s top node (Iris = uuSID 100.100.124).

The uuSID statement Cmap that is analogous to the clinical statement Cmap in Figure 8 is displayed in Figure 12.

In the Cmap in Figure 6, the linking phrases *may include* and *may be* that are used in the statement in Figure 8 represent connectors that have meaning in describing the elements of a statement that “might” be used to express relevant characteristics of an iris. These concepts, as defined in Table 1, are existential characteristics of an iris that can be described by a trained/experienced clinician and connected together to express the condition, characteristics, appearance, etc, of a patient’s iris. The “conditionality” of the linking phrases *may include* and *may be* are display-form elements that permit condensation and clarification of complex Cmaps that would otherwise require multiple propositional chains to express multiple Cmap lower or “atomic” nodes. In structuring a clinical statement using uuSIDs, the relevant descriptive elements are predominantly the pre-defined concepts expressed in uuSIDs. The meaning is expressed by the combination of concepts expressed by the chain of concepts selected from the Cmap, where the existential connector *is* could be used to replace *may include* or *may be* connectors that were used to describe the types of description that might be included in an iris finding.

In the example situation, the sequence of the chain of uuSIDs is not relevant or necessary to capture the meaning of the statement. Each and every descriptor is an existentially asserted characteristic of the context being described, where all of the specified descriptors are collectively required to completely specify the observation and its context. Computationally, the statements formulated in the Cmaps of Figures 8, 12, and 13 are equivalent.

**DOCUMENT FORMULATION AND ORDERING**

A document consists of a set of statements that are expressed by a clinician to describe the characteristics observed, measured, etc, during a clinical encounter, where each individual statement is expressed as completely and correctly as possible or desirable and contains an explicit representation of each and every concept required to contextualize and describe every

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*a A uuSID may be assigned to free text comments that may be created when a user encounters the need for a descriptive statement that has not been previously included in a model. The assignment of a uuSID for a text phrase enables the knowledge representation to be consistent, and it enables tracking of “free text comments” that are reused. This process may be used to enable continuous model analysis and improvement.*
Figure 11 Iris Cmap displayed using universally unique semantic identifier (uuSID) defined in Table 1.
### Table 1 Iris Definition Table

| Concept                | Definition                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| 1+                     | a scale of degree between 1 to beyond 4, with 1+ being the lowest definitive degree above “absent” or “trace” |
| 2+                     | a scale of degree between 1 to beyond 4, with 2+ being an intermediate degree |
| 3+                     | a scale of degree between 1 to beyond 4, with 3+ being the highest linear degree without non-linear complexity |
| 4+                     | a scale of degree between 1 to beyond 4, with 4+ being the highest degree above 3+ with added complexity |
| absent                 | degree with finding not observed or not manifested; different from masked or disguised |
| anatomy                | descriptive body structures that are observable                             |
| aperture               | a through-and-through planar opening that communicates between normally separate spaces |
| appearance             | an observed finding                                                          |
| atrophy                | a loss of normal tissue characteristics, such as loss of substance, color, elasticity, etc |
| blue                   | short wavelength primary color, resembling the color of the clear sky in the daytime |
| brown                  | a color term, denoting a range of composite colors produced by a mixture of orange, red, rose, or yellow with black or gray |
| iris collarette        | the persistent remnants of fetal iris stromal tissue circumferential to the iris sphincter |
| color                  | the degree and distribution of pigment in a tissue that contributes to its appearance |
| crypts                 | concavity of a tissue surface, similar to a “pit”; is not obviously through and through |
| degree                 | a descriptor or modifier that expresses amount, extent                       |
| flaccid                | lack of stiffness or elasticity                                              |
| flicked                | focal pigment inhomogeneity                                                  |
| flexibility            | the property of being bendable, supple                                       |
| green                  | longer wavelength than blue color                                           |
| grey                   | intermediate between white and black intensity                              |
| hazel                  | brownish-green color                                                         |
| IPE                    | iris pigment epithelium                                                      |
| iridectomy             | through-and-through aperture in the iris made with an excision of tissue    |
| iridotomy              | through-and-through aperture in the iris not made with an excision of tissue |
| iris                   | mesenchymal light control diaphragm that separates the anterior from posterior chamber |
| iris comments (free text) | iris clinical findings that are not currently Cmap modeled                  |
| iris finding           | clinical observations of the iris                                            |
| iris root              | peripheral iris where it connects to the anterior chamber angle              |
| location planar        | a descriptor or modifier that expresses location by extrinsic or intrinsic relation, meridional or azimuthal location |
| mass                   | an abnormal tissue that distorts, thickens, elevates, displaces the normal anatomy |
| mild                   | a subjective descriptor of degree of low severity                            |
| moderate               | a subjective descriptor of degree of intermediate severity                   |
| neovascularization     | new blood vessels, particularly capillaries, that are not in their normal anatomic location, configuration, etc |
| non-patent             | an aperture that is not through and through                                  |
| non-surgical           | a tissue modification not made in the course of a planned surgical procedure |
| normal                 | nonpathologic finding                                                       |
| OD observations        | observations of the right eye                                               |
| OS observations        | observations of the left eye                                                |
| patent                 | a through-and-through aperture                                              |
| periphery              | location at the outermost circumference of the coronal axis                 |
| persistent vascular strands | the persistent remnants of fetal iris vessels that may cross the pupil from collarette |
| pink                   | unsaturated red color                                                       |
| present                | a finding that is not absent                                                 |
| pupillary margin       | the axial margin of the pupil                                               |
| rubeosis               | “reddening”: the observation of new blood vessels on the iris surface and chamber angle |
| severe                 | a subjective descriptor of degree of high severity                           |
| size                   | a descriptor of dimensionality                                               |
| sphincter muscle       | a muscle the contraction of which closes an aperture or passageway           |
| stiff                  | lacking bendability or flexibility                                           |
| stroma                 | mesenchymal tissue                                                          |
| surgical               | planned tissue manipulation, removal, or modification                       |
| thick                  | increased tissue substance, typically planar, compared to “normal”           |
| thickness              | descriptor of tissue substance dimension and character                       |
| thin                   | decreased tissue substance, typically planar, compared to “normal”           |
| trace                  | a scale of degree between 1 and beyond 4, with trace being just barely perceptible but always apparent |
| transillumination      | transmittance of indirect light through a normally opaque tissue            |
encounter phenomenon that must be documented. The sequence of statements in a document is not relevant to the content of those statements or to the collective content. An inference engine could conceptually combine every statement in a document and construct a Cmap of the phenomena that are asserted to be present, true, observed, or measured that were included in a list of statements used by a clinician to describe a clinical encounter.

An unordered list of complete, fully contextualized statements can be ordered using organizing principles that are relevant to the reader or user of the clinical description. If, for example, one were to use the organizing principles that order the description of an iris (Figure 6), one might list all of the OU (both eyes) phenomena, followed by the OD (right eye) phenomena, followed by the OS (left eye) phenomena. Alternatively, however, one could define any set of ordering principles that are captured in the description and organize a clinical encounter in whatever manner is most productive to the user in a specific use context.

In addition to predesigned sequences, because a document is simply a collection of statements and every statement is a collection of phenomena, it is possible to order or reorder phenomena in statements and statements in documents by building hierarchical models of organizing principles that have usefulness in communicating phenomena or increasing efficiency or effectiveness in operations. We consider this capability an important characteristic of the proposed knowledge representation that is enabled by making all descriptive features explicit.

**LINGUISTIC TRANSLATION**

If documents are formulated in terms of uuSID concept identifiers, they are not tied to any specific natural language. In contrast, the HL7 clinical document architecture (CDA) approach begins with a user-readable natural language document, which is intended to record and communicate a clinician’s semantic intent and adds metadata to assist in computer parsing and processing. If uuSID-encoded concepts are mapped to linguistic display forms in multiple languages, concepts may be translated into whatever natural language equivalents have been defined. This capability may greatly extend the potential reach and benefit of documentation over that which is dictated or recorded originally in a natural language.

A table of the concepts and linking phrases used to formulate the blood pressure Cmap (Figure 2) is provided in Table 2. MedTrak Systems, Inc, uses this information to create data entry capabilities in their electronic health record (EHR). Examples of the entry screens are provided in Figures 14 and 15 for English and Italian, respectively. By providing definitions for concepts, uuSIDs can be translated into any languages desired without altering the meaning of the concept where the uuSID can be used to represent the concept in an interlingua and that identifier can be translated at runtime into the language of the user’s preference. We consider our approach to be more flexible than the approach adopted by the International Health Terminology Standards Development Organisation (IHTSDO, SNOMED CT) in which IHTSDO dictates the language and limits SNOMED CT to English and Spanish. We find the IHTSDO limitations on translation, which derive from their terminological classification architecture, to be unnecessarily restrictive. We suspect that their terminological management approach may potentially limit the capability to easily incorporate the contributions possible from research done by non–English-speaking clinicians and researchers.

**TRANSLATING MODELS INTO DOCUMENTATION MANAGEMENT SOLUTIONS**

The traditional approach to software development consists of a series of successive hurdles. At the beginning is a requirements-specification process.
**Table 2 Blood Pressure Concepts, Definitions, and Italian Translation**

| Concept       | Translation   | uuSID   | Definition                                                                 |
|---------------|---------------|---------|---------------------------------------------------------------------------|
| activity      | attività       | 100.101.100 | the state or quality of being active                                      |
| arm           | braccio            | 100.101.101 | an upper limb of the human body, connecting the hand and wrist to the shoulder |
| arterial      | arteria           | 100.101.102 | of, relating to, or being the blood in the arteries that has absorbed oxygen in the lungs and is bright red |
| BP            | pressione di sangue | 100.101.103 | “blood pressure” is the force of blood pushing against the walls of the arteries as the heart pumps blood |
| context of observation | contesto del osservazione | 100.101.104 | context describes the situation, conditions, circumstances, etc, that define the environment in which a measurement or observation is conducted, recorded, ascertained, etc |
| diastolic     | diastolico       | 100.101.105 | “diastolic” refers to blood pressure when the heart is at rest between beats |
| direct        | diretto          | 100.101.106 | without intervening influences, factors, etc, immediate                   |
| exercise      | esercizio        | 100.101.107 | activity that requires physical or mental exertion, especially when performed to develop or maintain fitness       |
| extremity     | membra           | 100.101.108 | part of a limb, as an arm or hand or a leg or foot                          |
| indirect      | indiretto        | 100.101.109 | coming or resulting otherwise than directly or immediately, as effects or consequences |
| instrument    | strumento        | 100.101.110 | a device for measuring the present value of a quantity under observation |
| laterality    | lateralità       | 100.101.111 | one side of the body or brain                                             |
| left          | sinistro         | 100.101.112 | of, relating to, directed toward, or located on the left side               |
| leg           | gamba            | 100.101.113 | a limb or an appendage of an animal, used for locomotion or support         |
| magnitude     | magnitudine      | 100.101.114 | a number assigned to a quantity so that it may be compared with other quantities |
| mmHg          | mmHg             | 100.101.115 | units of measurement denominated in millimeters of mercury                |
| observer      | osservatore      | 100.101.116 | individual making the observation                                         |
| other relevant context | altro contesto pertinenti     | 100.101.117 | a context of observation that is specified and may include the position and activity of the patient during the observation |
| patient identifier | identificatore del paziente     | 100.101.118 | a numeric, alphanumeric or other specifier that is used in patient records to identify a patient, issued by a provider of patient identifiers |
| place location | locale           | 100.101.119 | a specification of the place or location where the observation of the patient is made |
| position      | posizione        | 100.101.120 | the configuration in which the patient is observed which may include the patient being prone, sitting, or standing |
| prone         | prono            | 100.101.121 | a posture assumed by lying flat with the face forward in response to certain disorders of the spine or viscera |
| quantitative BP | pressione di sangue quantitativa | 100.101.122 | the pressure of blood against the walls of any blood vessel as specified by a quantitative ratio |
| resting       | in riposo        | 100.101.123 | patient is not engaged in an activity at the time they are observed |
| right         | destro           | 100.101.124 | of, relating to, directed toward, or located on the right side               |
| sitting       | seduto           | 100.101.125 | the act or position of one who sits, a period during which one is seated and occupied with a single activity, such as posing for a portrait or reading a book |
| standing      | in piedi         | 100.101.126 | performed or done from a standing position                                   |
| systolic      | sistolico        | 100.101.127 | “systolic” refers to blood pressure when the heart beats while pumping blood |
| time          | tempo specificato| 100.101.128 | a nonspatial continuum in which events occur in apparently irreversible succession from the past through the present to the future, specified in the form of a number representing a specific point on this continuum, reckoned in hours and minutes |
| units         | unità di misura | 100.101.129 | a precisely specified quantity in terms of which the magnitudes of other quantities of the same kind can be stated |
| vital signs   | segni vitali     | 100.101.130 | index of essential body functions, comprising pulse rate, body temperature, and respiration |
| is            | è                | 100.100.90.100 | predicate or linking phrase used in Cmaps to link to an equivalent or related concept or conceptual structure to communicate a type, a characteristic or a context |
| may           | può              | 100.100.90.101 | predicate or linking phrase used in Cmaps constructed to define information templates used to indicate that the nodes subordinate to the predicate are either optional or required if known |
| may have      | può avere        | 100.100.90.102 | predicate or linking phrase used in Cmaps constructed to define information templates used to indicate that a description may contain subordinate concept nodes or a subordinate Cmap that is necessary to fully express a clinical statement |
| may include   | può includere    | 100.100.90.103 | predicate or linking phrase used in Cmaps constructed to define information templates used to indicate that a description may contain subordinate concept nodes or a subordinate Cmap that is necessary to fully express a clinical statement |
| may be        | può essere       | 100.100.90.104 | predicate or linking phrase used in Cmaps constructed to define information templates used to indicate that a description may contain subordinate concept nodes or a subordinate Cmap that is necessary to fully express a clinical statement |
| must          | deve             | 100.100.90.105 | predicate or linking phrase used in Cmaps constructed to define information templates used to indicate that the concept nodes or structures subordinate to the predicate are required |
| must be       | deve essere      | 100.100.90.106 | predicate or linking phrase used in Cmaps constructed to define information templates used to indicate that a description must contain specific subordinate concept nodes or structures to fully express a clinical statement |
| must be expressed as | deve essere espresso come | 100.100.90.107 | predicate or linking phrase used in Cmaps constructed to define information templates used to indicate that the nodes subordinate to the predicate are required and must be expressed in a specific manner to correctly describe the measurement or observation |
| must include  | deve includere   | 100.100.90.108 | predicate or linking phrase used in Cmaps constructed to define information templates used to indicate that a description must contain specific subordinate concept nodes or structures to fully express the intentions for the clinical statement |
This process typically involves engineers interviewing users to ascertain the users’ needs. Inherent in the interview and specification process is the translation of those users’ needs. During the software engineering process, the users’ needs are captured and then expressed in the language of a technical expert. This process can introduce miscommunication and misunderstanding. A software quality process typically includes a verification step that seeks to test or evaluate the coherence between the requirement specifications and the users’ needs. Verification may identify errors in capture, translation, specification, etc, but when the process is not under the users’ direct control, it is possible that a difference may remain between the semantic intentions and assumptions of a user and the expressions of an engineer.

The traditional approaches to system development have been both costly and cumbersome and frequently result in continual incremental improvements that may or may not ever resolve into a “finished” solution, particularly in the presence of a continuously evolving situation like medical science. In most clinical situations, finding a meeting time that is convenient to a clinician with daily patient loads and the right software engineer can be difficult. There are clearly situations where specific skill sets help bridge the discipline gaps between medicine and computer science, but more typically clinicians have limited intimate experience with computer systems and computer experts have no formal training in medicine. Anything implicit or ambiguous can be “the enemy of the good.”

Cmaps present a tool that can enable a clinician to describe a clinical situation, information requirement, process, workflow, EMR template, etc, by defining concepts and connecting them with relationships under their own control with the guidance or aid of an information scientist or computer scientist facilitator. In an EMR, the goal is to capture the clinical evidence, diagnostic inferences, and diagnostic and interventional treatment plans in a way that places each element in an appropriate context for understanding and use. In conjunction with a facilitator to probe and assist in eliciting concepts and relation-
ships, we have found that clinicians are quite capable of explicitly expressing their information requirements directly in Cmaps.

The result of the requirements-specification process is a clean specification expressed in a computable form. The 4 critical elements to understanding the information requirements and their interrelationships in an EMR template are (1) concepts, (2) relationships, (3) logical propositions, and (4) template outline. These can be used directly to write rules that drive the information capture and display processes in a production EMR.

**DEMONSTRATION OF AN AUTOMATED TRANSLATION FROM A CONCEPTUAL MODEL TO ELECTRONIC HEALTH RECORD IMPLEMENTATION**

The Washington National Eye Center has developed and refined a number of Cmaps focused specifically on the field of ophthalmology. This work has demonstrated the advantage of enabling experts to directly manipulate a tool to express their expertise in the form of logical propositions. Working with a number of ophthalmologists, a collection of Cmaps was developed to describe the evidence collected during an ophthalmic examination. For example, a tear film Cmap required 75 propositions. The decision to begin by mapping measurements and observations was selected to enable later development of clinical decision support Cmaps using the described clinical observations, measurements, and findings.

The complexity of clinical description is substantial. In the case of a lens Cmap, approximately 180 propositions were required to describe the observations, measurements, and findings related to an ocular lens. Though that number of propositions cannot be easily viewed on a single-page Cmap, the network of concepts and relationships can be navigated using Cmap Tools (which can be downloaded at no charge at http://cmap.ihmc.us/download) and the complexity of that system of propositions can be converted into a structured checklist that can capture the elements of evidence necessary to describe a patient’s lens.

One specific complex lens statement that can be extracted by selecting a leaf node and its suptree and forming a propositional chain or graph that includes the selected note and all connected parent (hierarchically superior) notes and edges (relationships) requires 13 conceptual levels connected by relationships to diagram. In this particular example, the relationships are used to convey whether the next lower tier of concepts must or may include specific alternatives. For example, a haptic fixation may include capsular, suture, or suture fixation types of “haptic fixations.” In our experience in clinical modeling, a conceptual level may require the inclusion of multiple elements or types at each level of specificity. This can result in a clinical statement composed of many interacting descriptive propositions.

MedTrak Systems, Inc, has developed an automatic conversion of Cmaps into EMR templates for building physician checklists for problem-focused history and exam questions, nursing assessments and flowsheets, orders, workflow steps, patient aftercare instructions, and care pathways for interdisciplinary care. Figure 14 is a partial screen example of an information structure that MedTrak converted to address the capture of a blood pressure as described by the Cmap in Figure 2. Figure 15 shows the same screen translated into Italian.

**SUMMARY**

Medical knowledge structure and logic are highly complex. Simple hierarchical transactional and lexical models are not suitable to accurately reflect the practice of medicine as exemplified in clinical documentation and decision cycle analysis. Cmapping provides a tool that can significantly contribute to building a foundation for a dynamic, inclusive, collaborative, and cost-effective process of medical documentation that can meet the challenges of 21st-century medicine.

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8 A suptree is formed by selecting a leaf, detailed or bottom node (concept) in a Cmap and forming a propositional chain or graph that includes the selected note and all connected parent (hierarchically superior) notes and edges (relationships).