FEATURE

An Application of Cmaps in the Description of Clinical Information Structure and Logic in Electronic Health Records

Cmap 在描述临床信息结构和电子健康记录逻辑中的应用

Una aplicación de Cmaps en la descripción de la estructura y la lógica de la información clínica en los historiales médicos electrónicos

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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.

摘要

开发并执行有效和具备成本效益的计算机化医疗记录，能够显著提高医生的工作效率和知识管理水平，但是，这需要开发用于表述和分析医学知识和逻辑的全新模式。通过观察、检测及引导，医生获得患者信息，并将信息归纳为医学知识，但是，这是一项调查过程，医生与患者不存在交互作用。现今多数（如果不是全部的话）使用健康信息技术 (health information technology, HIT) 的方式均依赖于逻辑和数据结构，这使得医生彻底并有效地记录和存取以实验为根据的患者数据受到较大限制，因为信息总是以假定（而非明确说明）概念及其含义的关系的方式进行组织。Cmapping 以图解的方式捕获并显示专业认知知识，它易于理解和修改，并为获得动态、归纳和相容的临床文件编制和研究方法奠定基础。医疗判定分析以及典型的医学知识模型化范例均能够以 Cmap 格式提供。在 Cmap 中捕获的知识结构，能够以命题逻辑直接表达，并能够使用转换为 Cmapped 格式的临床表述，定义临床证据文件编制和分析的描述逻辑，并可依次映射为多种自然语言。上述描述性逻辑方法可用于公式化数字讯息和文件，并自动化将用命题逻辑公式表示的描述规格转换为可用的电子健康记录解决方案以捕获并报告临床发现的程序。经证实，使用 Cmap 推导医生的认知知识，以建立医护点临床文献筛选机制，可有效减少将医生的知识纳入工作系统所需的时间和成本，并可使用 Cmap，消除规则编写过程对 HIT 专业知识的需求。

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 medición 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 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 información de contenido experto, el cual resulta sencillo de comprender y modificar y, además, sienta las bases de un método dinámico, inductivo e integrador de la documentación e investigación clínicas. Los fundamentos del análisis de las decisiones médicas, junto con la creación de modelos de muestras representativas del conocimiento médico, se presentan en forma de mapa conceptual. Las estructuras de la información capturadas en los mapas conceptuales se pueden expresar directamente mediante la lógica proposicional, de forma que permita convertir las expresiones clínicas a utilizar en mapas conceptuales, a fin de definir una lógica descriptiva para la documentación y el análisis de las evidencias clínicas que, a su vez, se pueden cartografiar en múltiples lenguajes naturales. Este planteamiento de lógica descriptiva se puede emplear para elaborar mensajes y documentos digitales y para automatizar el proceso de conversión de especificaciones descriptivas formuladas en lógica proposicional en soluciones electrónicas operativas de historias clínicas destinadas a la captura y notificación de las visitas clínicas. También se ha mostrado que mediante mapas conceptuales destinados a obtener conocimientos de contenidos a partir de los médicos, con el fin de crear pantallas de documentación clínica en el lugar de atención, se puede reducir significativamente el tiempo y los costes necesarios para introducir el conocimiento del médico en los sistemas operativos, y que, mediante los mapas conceptuales, se elimina la necesidad de experiencia en el uso de las TIS a la hora de procesar la codificación de reglas.

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 interventional 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.[3-5] 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)."[5] 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.[4,5] 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.

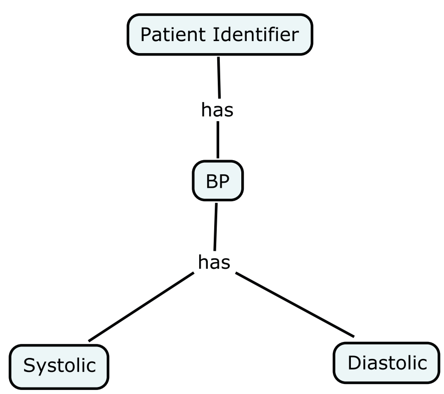

Figure 1 Simple blood pressure description model.

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

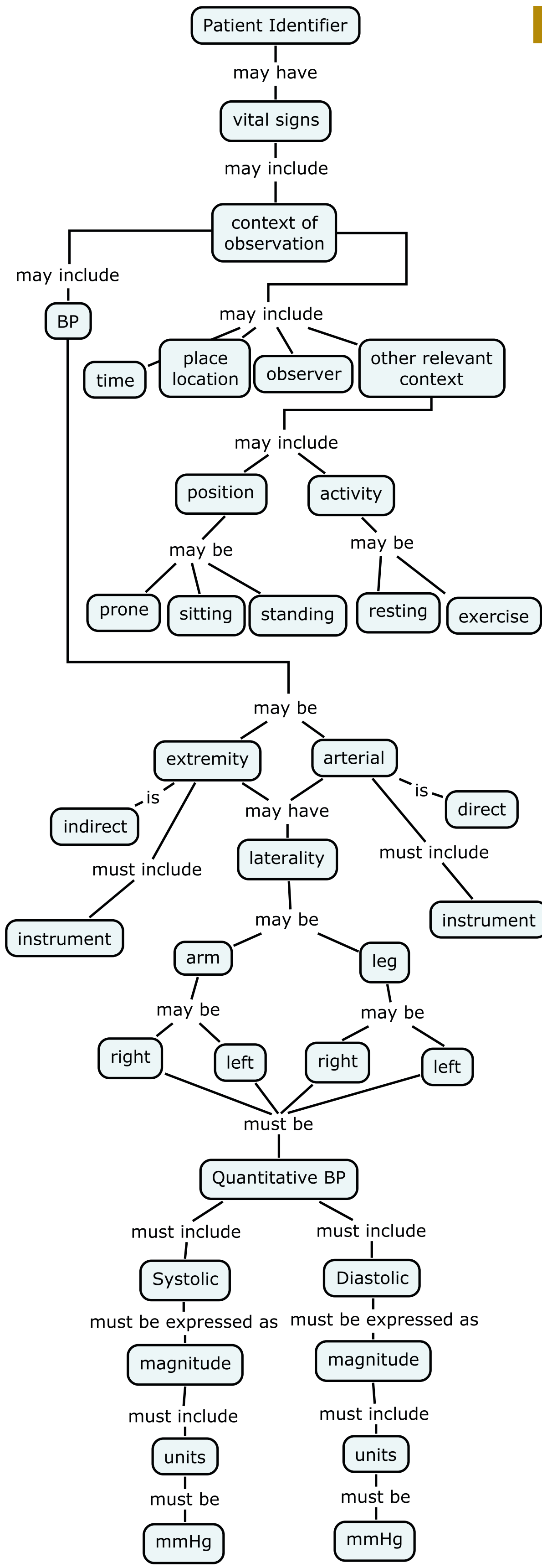

Figure 2 Complex blood pressure description model.

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

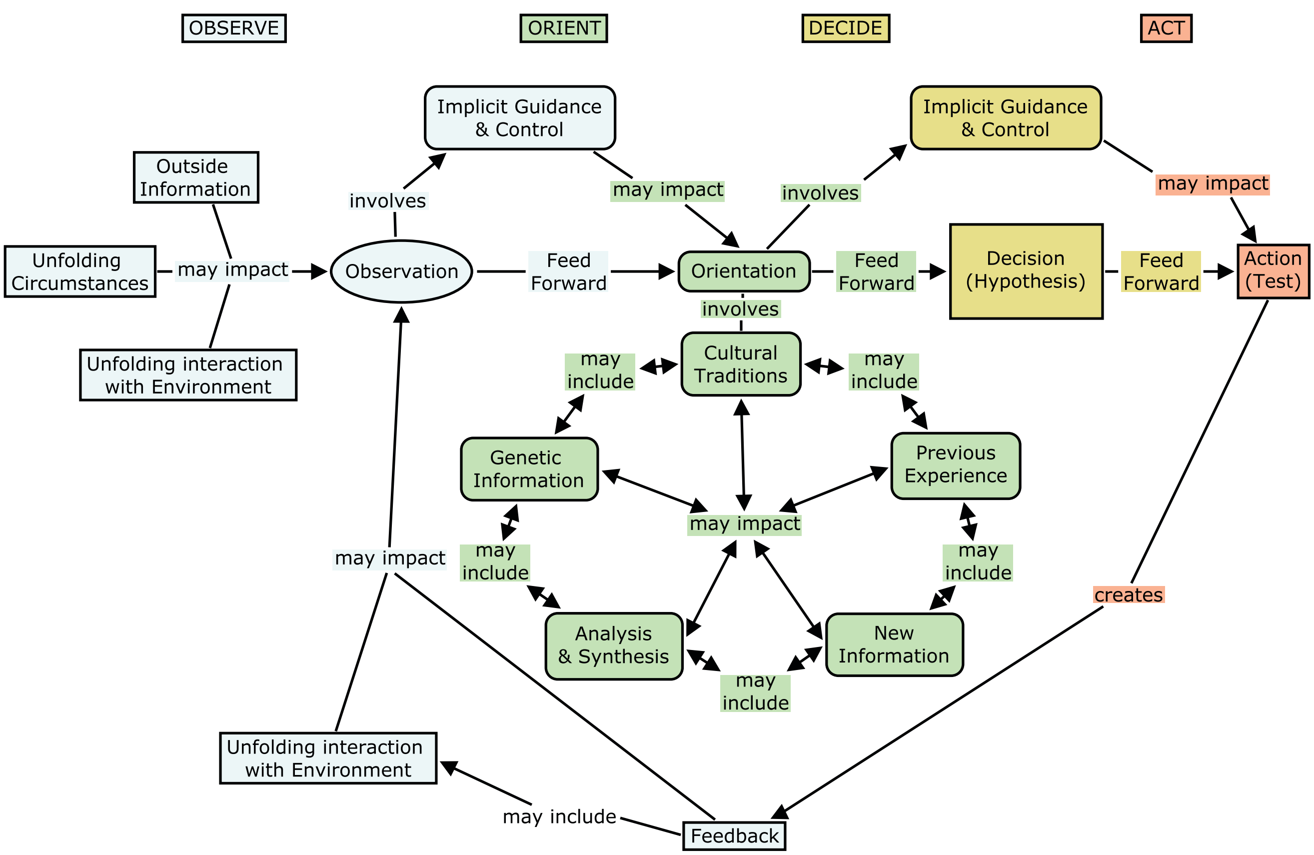

Figure 3 Observation-Orientation-Decision-Action Loop.

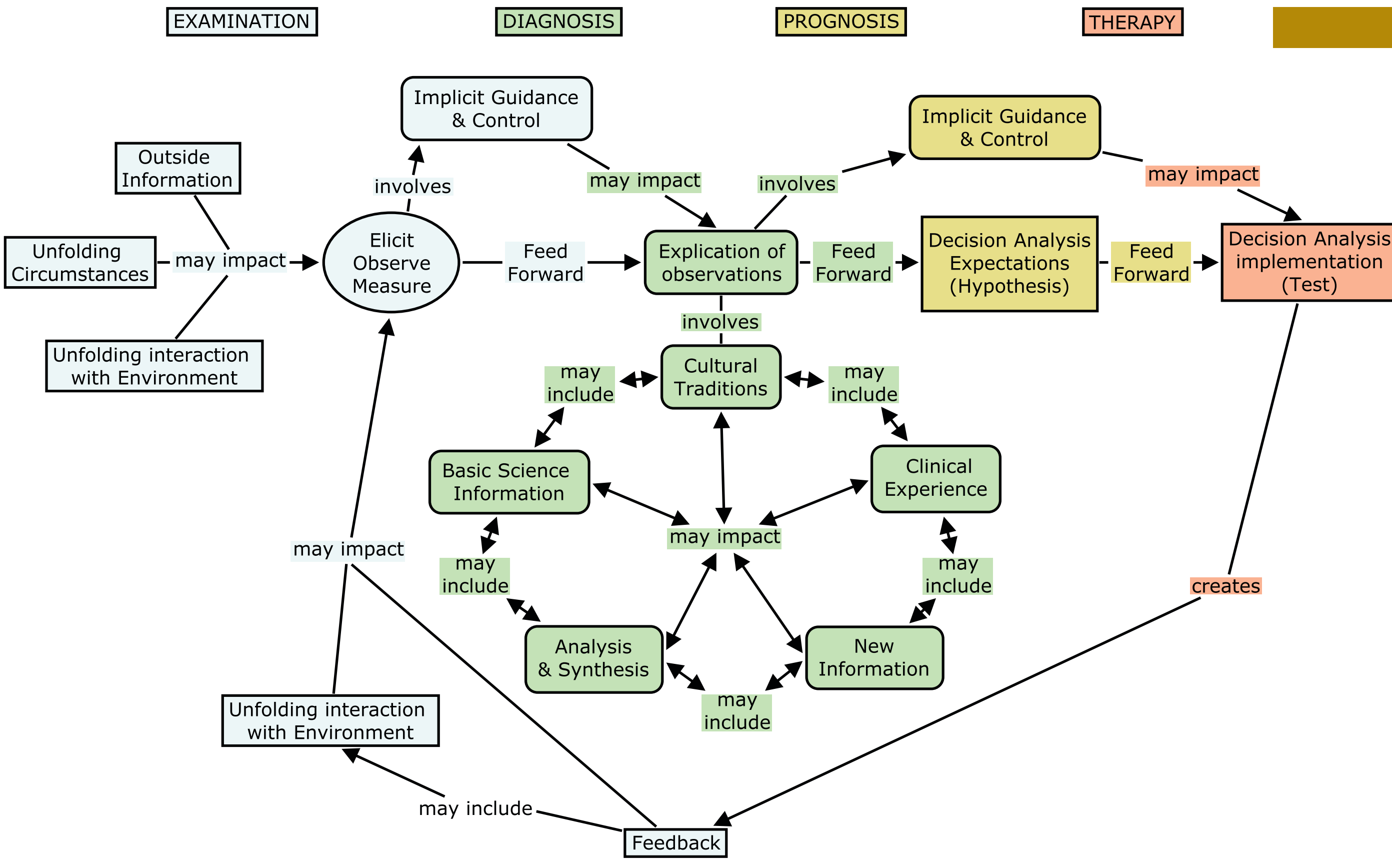

Figure 4 Medical decision cycle.

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-

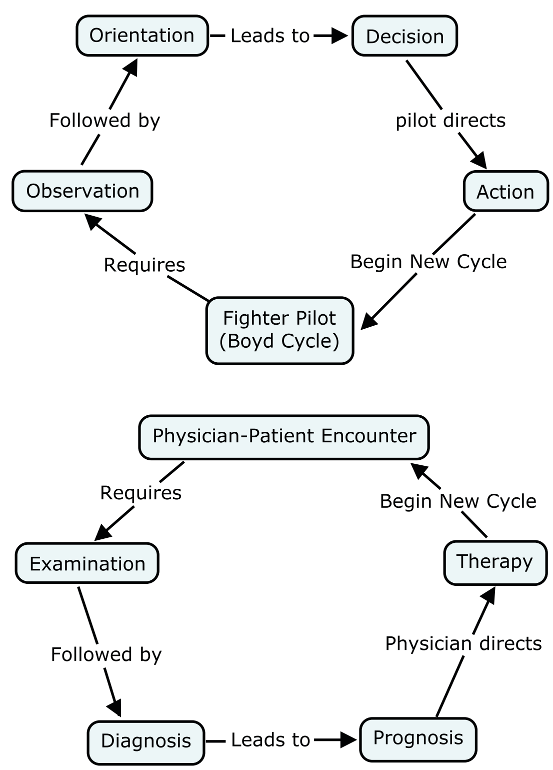

Figure 5 Observation-Orientation-Decision-Action Loop—medical decision cycle.

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

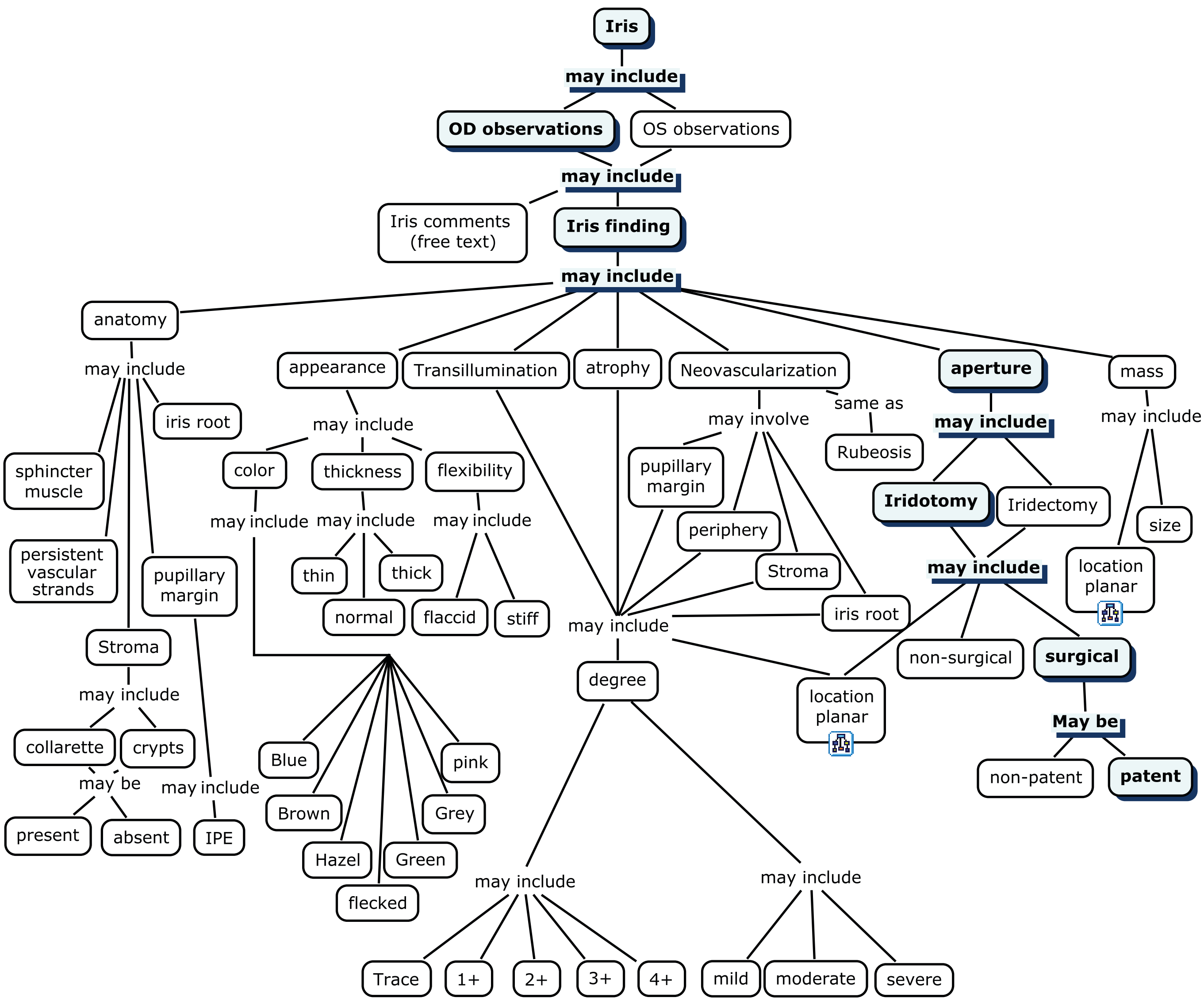

Figure 6 Iris description model.

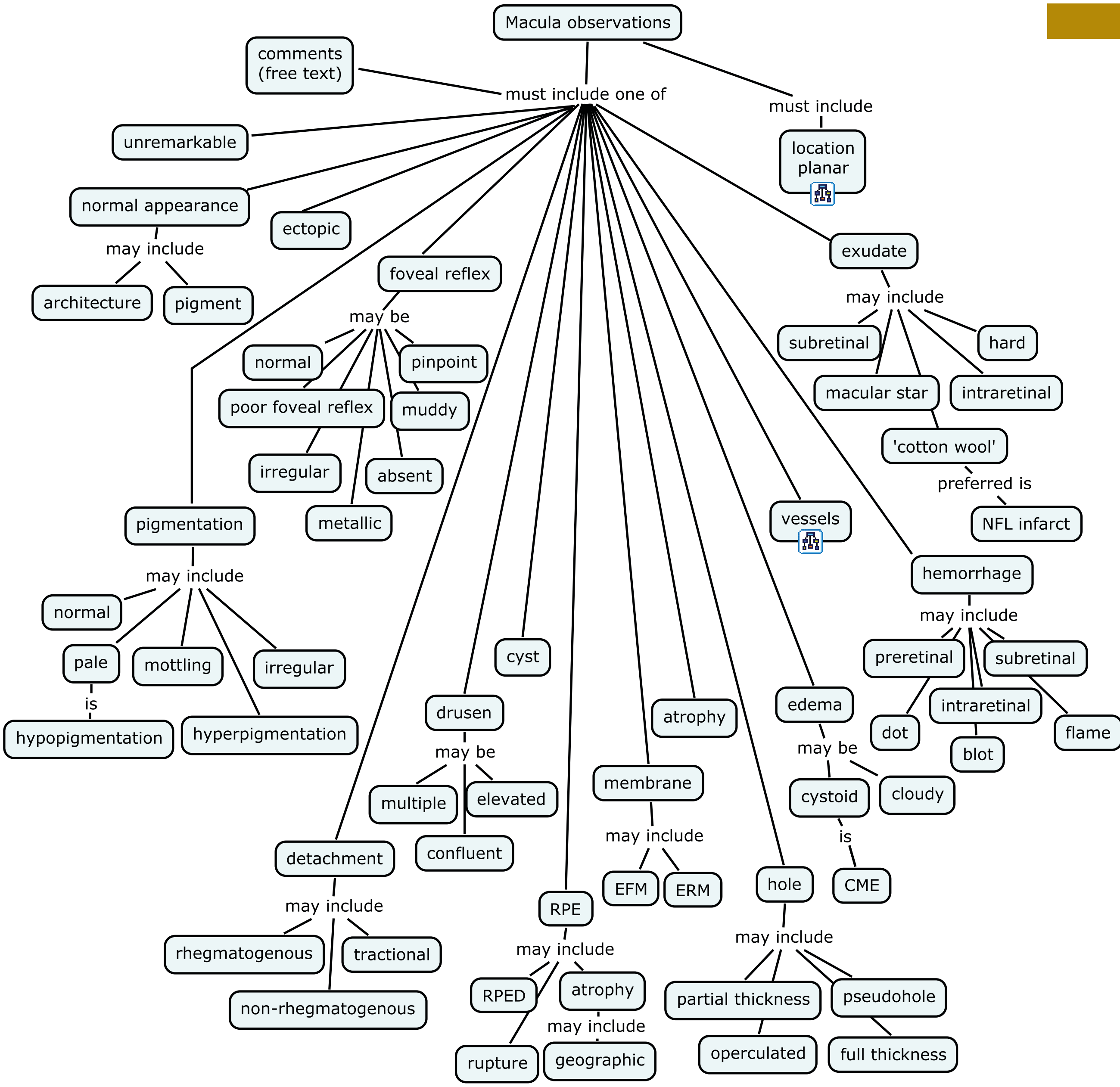

Figure 7 Macula lutea description model.

Figure 8 Iris clinical statement.

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,

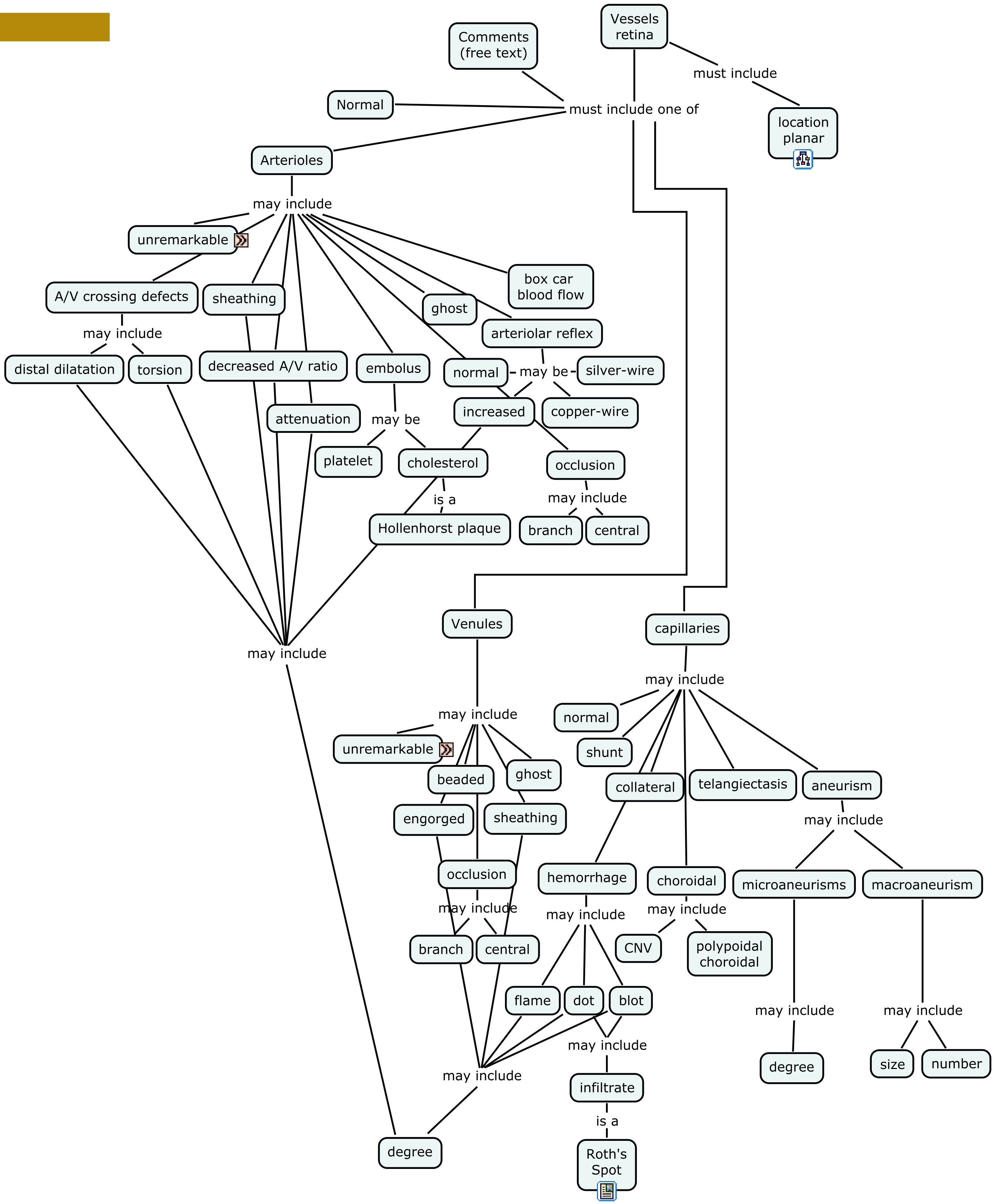

Figure 9 Vessels retina linked Cmap from Figure 7.

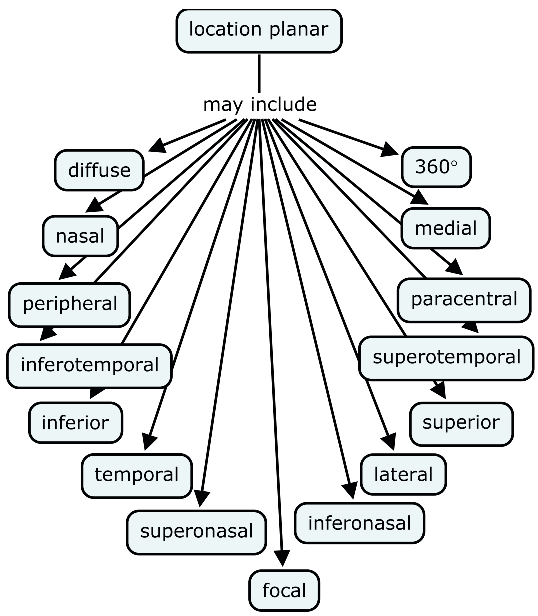

Figure 10 Location planar linked Cmap from Figures 6, 7, and 9.

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.[a] 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

[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.

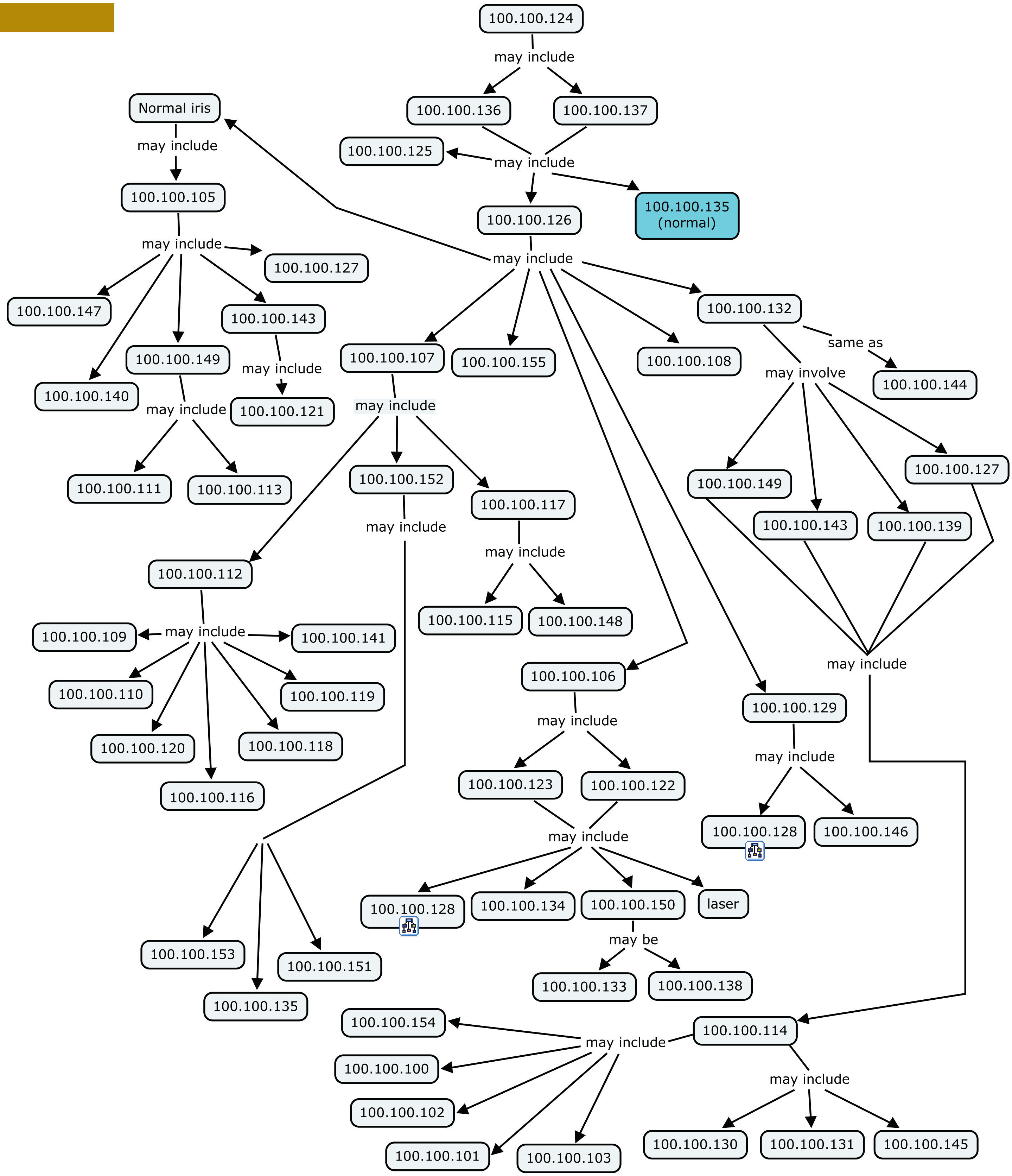

Figure 11 Iris Cmap displayed using universally unique semantic identifier (uuSID)defined in Table 1.

Table 1 Iris Definition Table

Concept	uuSID	Definition
1+	100.100.100	a scale of degree between 1 to beyond 4, with 1+ being the lowest definitive degree above "absent" or "trace"
2+	100.100.101	a scale of degree between 1 to beyond 4, with 2+ being an intermediate degree
3+	100.100.102	a scale of degree between 1 to beyond 4, with 3+ being the highest linear degree without non-linear complexity
4+	100.100.103	a scale of degree between 1 to beyond 4, with 4+ being the highest degree above 3+ with added complexity
absent	100.100.104	degree with finding not observed or not manifested; different from masked or disguised
anatomy	100.100.105	descriptive body structures that are observable
aperture	100.100.106	a through-and-through planar opening that communicates between normally separate spaces
appearance	100.100.107	an observed finding
atrophy	100.100.108	a loss of normal tissue characteristics, such as loss of substance, color, elasticity, etc
blue	100.100.109	short wavelength primary color, resembling the color of the clear sky in the daytime
brown	100.100.110	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	100.100.111	the persistent remnants of fetal iris stromal tissue circumferential to the iris sphincter
color	100.100.112	the degree and distribution of pigment in a tissue that contributes to its appearance
crypts	100.100.113	concavity of a tissue surface, similar to a "pit"; is not obviously through and through
degree	100.100.114	a descriptor or modifier that expresses amount, extent
flaccid	100.100.115	lack of stiffness or elasticity
flecked	100.100.116	focal pigment inhomogeneity
flexibility	100.100.117	the property of being bendable, supple
green	100.100.118	longer wavelength than blue color
grey	100.100.119	intermediate between white and black intensity
hazel	100.100.120	brownish-green color
IPE	100.100.121	iris pigment epithelium
iridectomy	100.100.122	through-and-through aperture in the iris made with an excision of tissue
iridotomy	100.100.123	through-and-through aperture in the iris not made with an excision of tissue
iris	100.100.124	mesenchymal light control diaphragm that separates the anterior from posterior chamber
iris comments (free text)	100.100.125	iris clinical findings that are not currently Cmap modeled
iris finding	100.100.126	clinical observations of the iris
iris root	100.100.127	peripheral iris where it connects to the anterior chamber angle
location planar	100.100.128	a descriptor or modifier that expresses location by extrinsic or intrinsic relation, meridional or azimuthal location
mass	100.100.129	an abnormal tissue that distorts, thickens, elevates, displaces the normal anatomy
mild	100.100.130	a subjective descriptor of degree of low severity
moderate	100.100.131	a subjective descriptor of degree of intermediate severity
neovascularization	100.100.132	new blood vessels, particularly capillaries, that are not in their normal anatomic location, configuration, etc
non-patent	100.100.133	an aperture that is not through and through
non-surgical	100.100.134	a tissue modification not made in the course of a planned surgical procedure
normal	100.100.135	nonpathologic finding
OD observations	100.100.136	observations of the right eye
OS observations	100.100.137	observations of the left eye
patent	100.100.138	a through-and-through aperture
periphery	100.100.139	location at the outermost circumference of the coronal axis
persistent vascular strands	100.100.140	the persistent remnants of fetal iris vessels that may cross the pupil from collarette
pink	100.100.141	unsaturated red color
present	100.100.142	a finding that is not absent
pupillary margin	100.100.143	the axial margin of the pupil
rubeosis	100.100.144	"reddening": the observation of new blood vessels on the iris surface and chamber angle
severe	100.100.145	a subjective descriptor of degree of high severity
size	100.100.146	a descriptor of dimensionality
sphincter muscle	100.100.147	a muscle the contraction of which closes an aperture or passageway
stiff	100.100.148	lacking bendability or flexibility
stroma	100.100.149	mesenchymal tissue
surgical	100.100.150	planned tissue manipulation, removal, or modification
thick	100.100.151	increased tissue substance, typically planar, compared to "normal"
thickness	100.100.152	descriptor of tissue substance dimension and character
thin	100.100.153	decreased tissue substance, typically planar, compared to "normal"
trace	100.100.154	a scale of degree between 1 and beyond 4, with trace being just barely perceptible but always apparent
transillumination	100.100.155	transmittance of indirect light through a normally opaque tissue

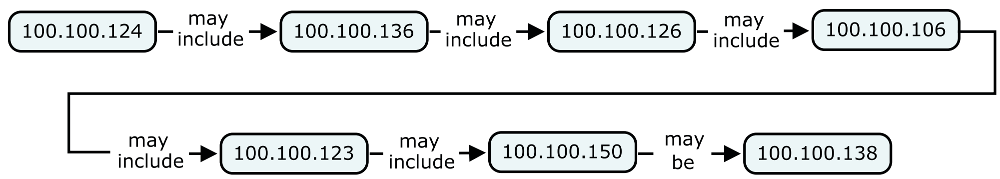

Figure 12 Iris clinical statement.

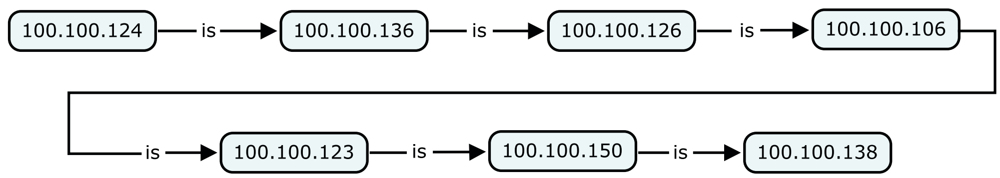

Figure 13 Iris clinical statement in the existential form characteristic of a finding list.

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 pertinente*	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 liking 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 liking 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 liking 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 liking 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 liking 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

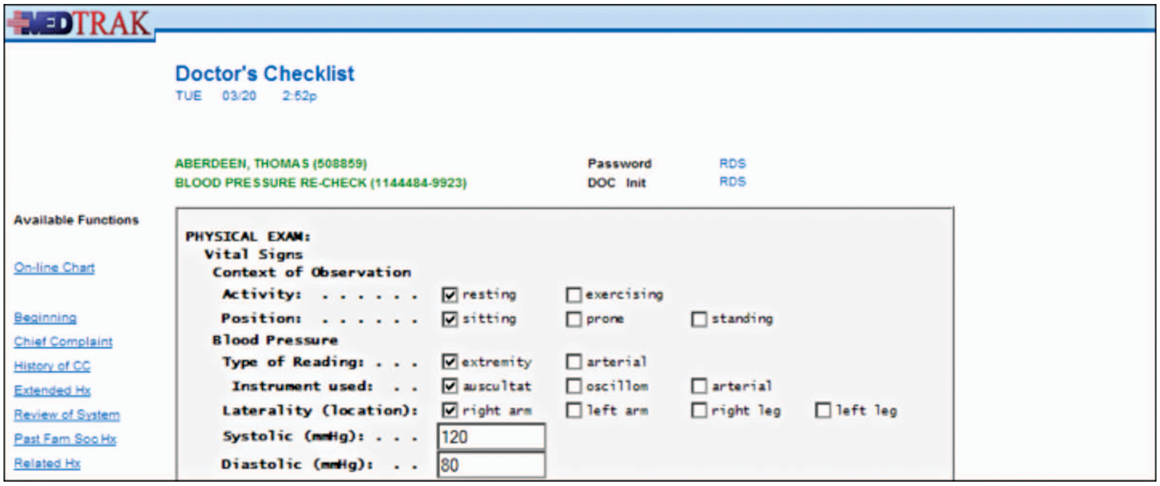

Figure 14 MedTrak Systems, Inc, point-of-care EMR blood pressure template.

Figure 15 MedTrak Systems, Inc, point-of-care electronic medical record blood pressure template (Italian).

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 relationships, 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[b] consists of 36 propositions that describe both the characteristics of the observation and the organizing principles associated with contextualizing an observation. That specific statement may be used to describe either an OD (right) or OS (left) lens specification in which a patient might have an intraocular lens with fixation in the posterior chamber, which is described as a capsular haptic fixation involving a single haptic (lens fixation element) suspended in a meridional orientation that is temporally oblique. This example includes both evidentiary elements and organizing principles. It 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, sulcus, 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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[b] 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).