J Med Syst (2010) 34:829–842
DOI 10.1007/s10916-009-9297-2

ORIGINAL PAPER

A Health Examination System Integrated with Clinical Decision Support System

Kuan-Liang Kuo · Chiou-Shann Fuh

Received: 2 January 2009 / Accepted: 13 April 2009 / Published online: 1 May 2009

Abstract Health examinations play a key role in preventive medicine. We propose a health examination system named Health Examination Automatic Logic System (HEALS) to assist clinical workers in improving the total quality of health examinations. Quality of automated inference is confirmed by the zero inference error where during 6 months and 14,773 cases. Automated inference time is less than one second per case in contrast to 2 to 5 min for physicians. The most significant result of efficiency evaluation is that 3,494 of 4,356 (80.2%) cases take less than 3 min per case for producing a report summary. In the evaluation of effectiveness, novice physicians got 18% improvement in making decisions with the assistance of our system. We conclude that a health examination system with a clinical decision system can greatly reduce the mundane burden on clinical workers and markedly improve the quality and efficiency of health examination tasks.

Keywords Decision support systems · Clinical preventive medicine · Health promotion · Preventive health services · Diagnostic errors

K.-L. Kuo
Family Medicine Department, RenAi Branch,
Taipei City Hospital,
10F, No. 10, Sec. 4, RenAi Road,
Taipei City 106 Taiwan, Republic of China
e-mail: d93009@csie.ntu.edu.tw

K.-L. Kuo · C.-S. Fuh (✉)
Department of Computer Science and Information Engineering,
National Taiwan University,
No. 1, Sec. 4, Roosevelt Road,
Taipei City 10617 Taiwan, Republic of China
e-mail: fuh052006@yahoo.com.tw

Introduction

Health examinations can detect health disorders early and lead to prompt evaluation and treatment. Thus, health examination is important in the field of public health. A health report, which comprises the results of various tests and a summary of abnormal findings and related recommendations, is the most important product of a health examination. Mistakes occurring in the workflow of a health examination may cause a defective report, which can cause serious problems. We propose Health Examination Automatic Logic System (HEALS) to improve the total quality of health examinations [1]. This paper particularly focuses on the issues relating to the processing of the health report. We have presented the preliminary studies of HEALS by posters in 2006 American Medical Informatics Association Spring Congress [2, 3]. However, this paper will describe and evaluate the health examination system beyond the scopes of above brief works.

Background

Environment

HEALS has been developed at the Family Medicine Department of Taipei Municipal Jen-Ai Hospital (current Ren-Ai Branch of Taipei City Hospital) since 1995. This hospital is an 800-bed teaching hospital in Taipei, Taiwan. The users of HEALS are mostly the members of Family Medicine Department including clinical physicians, nurses, and assistants.

Health examination

Health examinations play an important role in preventive medicine. Evidence-based clinical preventive services have been demonstrated to be important elements in healthcare [4, 5].

In Taipei City Hospital, the health examinations are designed as "packages" for the convenience and needs of people. The contents of these packages are included under the recommendation of the United States Preventive Services Task Force [6] and the common needs of the local population. Health examination packages can satisfy most population groups, which can be roughly categorized as governmental screening projects, clinical indications, special high-risk groups, socioeconomic considerations, and even personal desires. Beyond the content of packages, optional checkup items are provided for more specific clinical or individual requirement.

Except for the health examination packages provided by governmental screening projects, customers have to pay their own expenses for health examinations. In some aspects, this type of health examination service is an instance of consumer-driven healthcare.

Problems to solve

Guaranteeing the quality of health reports is an important issue in health examinations. In the past, in order to meet such a requirement, clinical workers had to fetch health examination data from scattered sources, such as medical charts or a hospital information system. The health examination results for a person are mostly normal or not significantly abnormal. Critical abnormal results are relatively few. One major job of a clinical professional in generating health reports is checking and interpreting the examination results of individuals. The verification process ensures valid examination results and clinical diagnoses. Thus to generate a health report, clinical workers have to concentrate on many tedious tasks. In this circumstance, we consider the burdens of the daily routines of clinical workers, human resource officers, and customers. Repetitive and uninteresting workloads are labor intensive and mostly boring. Healthcare professionals such as physicians and nurses soon lose their responsiveness to these monotonous jobs. In addition, human resource policy dictates minimal manpower consumption for health examination affairs. Furthermore, health reports generated by different clinical workers manually, that is, without computer assistance, can neither maintain consistent quality nor satisfy most customers.

Prototypical system for health examination

Before HEALS, a very prototypical health examination system was incorporated into a relatively simple health examination package, wherein only physical examination results, blood routine, and urine analysis needed to be interpreted to make final diagnoses and recommendations. The prototypical system is standalone since the hospital information system (HIS) was not yet available at the time. Inevitably, all data required human entry. In this system, a simple interpretation was made by direct comparison between clinical data and reference values followed by outputting an alert for any anomaly encountered. Recommendations about the anomalies were selected from a menu list by physicians. The success of this prototypical experiment demonstrated the feasibility and value of a health examination system. In the current stage of development, we have set up a model of information flow in a health examination system and performed primary system analysis.

Related work by others

The knowledge representation model is a critical issue for CDSS development. In our review, at least 11 types of representation models including Arden Syntax, PROforma, GLIF, GASTON, etc. were studied and used to encode clinical guidelines or knowledge [7, 8]. We analyzed the crucial primitives of these representation models. Primitives are categorized by the task types they intend to represent. *Decision* and *action* are two major primitives. A decision is a logical path based on predefined rules. An action is a clinical task that is indicated by a decision.

A decision is used to represent the process of medical decision making. Logical criteria to make decisions are the context of a decision primitive. Arden Syntax encodes this process in the logic slot of a medical logic module (MLM). GLIF has a decision step. Nevertheless, only a finite amount of clinical data is available in a health examination package. In some cases, insufficient clinical data make definitive decisions impossible and thus further choices are necessary. In GLIF, an additional *choice* step provides "user decision" which is separate from "automatic decision".

An *action* is used to represent clinical tasks to be performed, maintained, or avoided as recommended by a decision. Arden Syntax provides the action slot in MLM. GLIF also has an action step for similar purposes. Clinical tasks can be clinical interventions, evaluations, alerts, recommendations, etc.

We aim to provide a solution for improving the workflow of heath examinations. To achieve our goal, we propose a simple and clear knowledge representation model, which can completely satisfy the needs of HEALS.

Design objectives

Reduce the mundane daily tasks of clinical workers

Most of healthcare workers' daily tasks in health examinations are repetitious and noncreative. One of the important purposes of HEALS is to relieve clinical workers from such tasks and allow experts to focus on irreplaceable and innovative affairs.

Improve the quality of health examination

Health information technology has shown many important benefits on health care quality [9–14]. HEALS establishes a standardized information flow model for health examinations. This standardization eliminates probable human errors and improves the quality of health examinations.

Improve the efficiency of health examination

Iterative data collection, filtering, transformation, merging, interpretation, and presentation are important elements of the health examination flow. We insist that an effective health examination should take advantage of information technologies to ameliorate such tedious operations.

Provide education for novice clinical workers

HEALS CDSS provides a computerized implementation of clinical guidelines, expert consensus, and local experiences. The output text of CDSS is composed of diagnoses, medical recommendations, and lifestyle recommendations for clinical disorders. Clinical experts verify the output during the development of HEALS. Novice clinical workers using HEALS daily can take the output texts as references for specific domains.

Eliminate common mistakes in health reports

Four common mistakes in processing health reports are addressed: failure to correctly detect problems from multiple examination results, failure to give proper suggestions for further medical management or life style modification, failure to write a well edited report, and failure to meet the deadline for sending reports. Eliminating these problems is obviously crucial.

Provide services beyond the territory boundary

The versatile services of HEALS should be accessible on demand. We want to design the architecture to give indistinguishable user experiences to both remote and local users. They can access HEALS in the same way and obtain the same services regardless of their locations. Health experts can process health reports and miscellaneous operations in different medical settings or at home. The services of HEALS should be uniform between rural and urban sites of usage.

System description

Architecture

HEALS consists of four major parts: user interface, CDSS, report presentation subsystem, and data application subsystem (Figs. 1 and 2). A user interface is designed to provide optimal facilities for data entry, report generation, and information query. CDSS is the crucial component of HEALS and will be described in detail in next paragraph. A report presentation subsystem aims to provide final reports with high flexibility and quality. A user-defined presentation template based on HTML makes that feasible. A data application subsystem is provided to facilitate frequently required statistical reports or charts.

CDSS is designed to be a direct aid to clinical decision making [15]. Evidence suggest that CDSS can lead to more appropriate clinical decision making and improve the quality of care [16–18]. We integrate CDSS into HEALS that works in a distributed environment to provide patient specific decision support. HEALS retrieves patient specific data from hospital information systems to establish data repositories for CDSS. We introduce HEALS CDSS by its components: content base, rule base, and reasoning engine [19, 20].

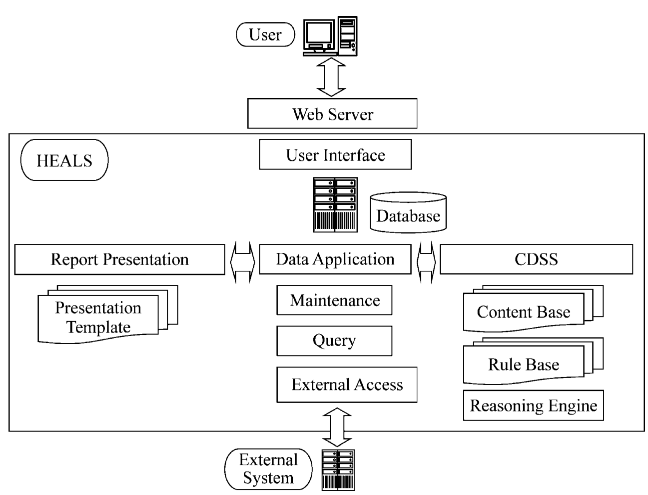

Fig. 1 HEALS and the related distributed environment. User interface, CDSS, report presentation subsystem, and data application subsystem are four major parts of HEALS. Users access HEALS via a Web interface. External system is the data source that provides result data of various examinations and administration data to HEALS

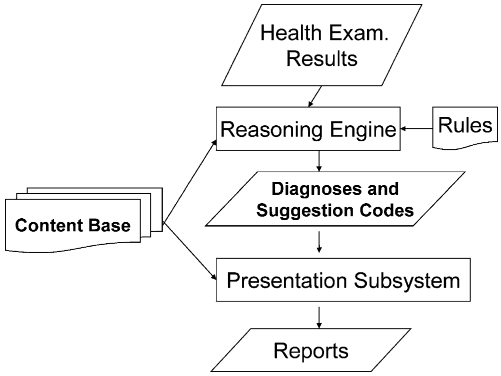

Fig. 2 Workflow of the reasoning engine and presentation subsystem of HEALS. The inference processes of the reasoning engine are introduced in Sections Content Base and Rule Base and Reasoning Engine. The presentation subsystem formats the automated inference output into a humanistic layout

Content base

The content base of HEALS is a set of domain specific information including reference values of laboratory tests, medical terms thesauri [21, 22], and recommendation text. In our experience, reference values of laboratory tests are one of the most frequently modified pieces of information. They are influenced by updates of diagnosis guidelines or consensus, laboratory machine upgrades, and local practical knowledge. Medical terms are grouped by related examination items. These medical terms play an important role in both data entries and further automatic reasoning task. Recommendation texts can be categorized into two parts, medical recommendations and lifestyle recommendations. Medical recommendations provide further medical intervention requirements to the patients. Lifestyle recommendations give lifestyle modification suggestions, such as ceasing unhealthy habits, eating a balanced diet, or getting adequate exercise. Recommendation texts are the most customized part of the content base. Essentially, its contents depend on medical guidelines and academic consensuses. Local experiences and personal opinions can also play important roles in the designation of recommendation texts.

Rule base and reasoning engine

The rule base contains inference logics for interpreting specific health examination results. The rules we proposed in HEALS are based on propositional logic. To achieve the mission of clinical decision support, the reasoning engine, rule base, and content base are the three major components. Logically these three components work cooperatively and they are undivided during the run time. In the initial phase of development, the intuitive way to implement a workable system may be by embedding rules and content data into the reasoning engine program. However, this procedural approach will soon exhaust its initial benefit while the software system grows in scale. During the prototype stage, HEALS CDSS uses a procedural approach for focusing on fast development and urgent online requirement without losing usability. Then, HEALS CDSS was rewritten with a declarative approach after the prototype stage [23]. Physically, the reasoning engine is clearly separate from the rule base and content base. The inference logic and domain content knowledge are confined to the rule base and the content base. This modularity has obvious advantages for further extending and refining the system.

Programmers of HEALS can improve the algorithm of the reasoning engine without considering the existing rule base and content base. Medical experts need not take care of the algorithm of the reasoning engine but focus only on their domain to design clinical decision rules and content base. Although the reasoning engine, rule base, and content base are designed and maintained separately, they still perform the automated inference seamlessly.

Simplicity is everything. A rule is composed of three components: a rule command, a rule name, and a sentence. Only four types of rule commands are introduced to construct the rule base of HEALS CDSS. Either *limitdef* or *rangedef* command declares atomic rules, which represent the constraints of health examination variable values (e.g., UWBC: urine white blood cell count). Commands *clausedef* and *ruledef* are used in declaring the composition of propositional logics. The rule name is a symbol with Boolean value. The sentence in a rule declared by *limitdef* or *rangedef* contains a health examination variable and simple comparison. Under the design philosophy of simplicity and clarity, sentence of command *clausedef* is purely a disjunction of literals; sentence of command *ruledef* is purely a conjunction of literals. Parentheses enclosure is not defined in our syntax. Every sentence of propositional logic is logically equivalent to a conjunction of disjunctions of literals, that is, a sentence in conjunctive normal form [23]. Thus, it is easy to see that combination of *clausedef* rules and *ruledef* rules can completely define propositional logics. In the real world during the daily practice, these rule syntaxes are enough to represent the rules used in interpreting health examination results.

We use a part of the algorithm of interpreting the results of hepatitis B test as the example to demonstrate how to design the rules and how the rules work (Fig. 3). In this example, we need information of previous hepatitis B tests to make differential diagnoses. The literals are defined as:

limitdef HBSAG_neg HBSAG = =“–”
limitdef HBSAB_neg HBSAB = = “–”
limitdef HBCAB_pos HBCAB = = “+”
limitdef OLD_HBSAG_pos HBSAG = = “+”

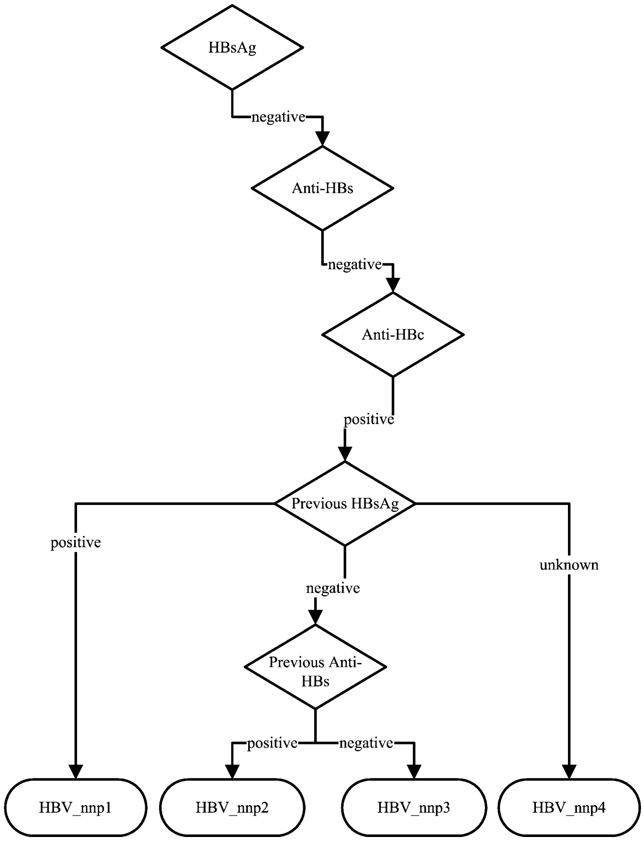

Fig. 3 Automated inference process about hepatitis B related tests. This figure illustrates the inference paths under the condition that both Hepatitis B surface antigen (HBsAg) and surface antibody (Anti-HBs) are negative as well as core antibody (Anti-HBc) is positive. In this case, previous HBsAg and Anti-HBs data are also considered to reach the final judgment

limitdef OLD_HBSAG_neg HBSAG = = "–"
limitdef OLD_HBSAB_pos HBSAB = = "+"
limitdef OLD_HBSAB_neg HBSAB = = "–"

If previous HBsAg is positive, diagnosis of chronic hepatitis B is more likely. If previous HBsAg is negative, we would like to know the result of previous Anti-HBs test. Positive previous Anti-HBs test confirms the immunity from natural virus. Negative previous Anti-HBs test makes the diagnosis still indefinite.

ruledef HBV_nnp HBSAG_neg && HBSAB_neg && HBCAB_pos
ruledef HBV_nnp1 HBV_nnp && OLD_HBSAG_pos
ruledef HBV_nnp2 HBV_nnp && OLD_HBSAG_neg && OLD_HBSAB_pos
ruledef HBV_nnp3 HBV_nnp && OLD_HBSAG_neg && OLD_HBSAB_neg
ruledef HBV_nnp4 HBV_nnp && OLD_HBSAG_unknown

The complex interpretation process of this example can be clearly represented by our decision rules within reasonable steps. After the reasoning engine of our decision support system executes the decision rules, the end rules will obtain a Boolean value. If it is true, the reasoning engine outputs a set of codes. An action will be triggered to perform mapping in knowledge base immediately. The diagnosis and related recommendation context will be retrieved to synthesize the final human-readable text.

Database contains health examination results of cases

The health examination results database imports the data from the HIS after appropriate data mapping and format conversion of corresponding fields. All imported data are editable by users via the user interface of HEALS. This data collection mechanism takes into account both efficiency and flexibility. Health examination data imported from HIS eliminate the probable human entry errors and conserve user time. User editable data fields give clinical workers the best opportunity to modify the health examination data. From the viewpoint of HEALS CDSS, the health examination results database is the data source of its algorithm.

Implementation

To accommodate the requirements of our design goals, a Web-based user interface is the most reasonable choice. Users can get the services of HEALS via ubiquitous web access through web browsers (Figs. 4 and 5). The web-based application needs only server-side maintenance. Users can enjoy the improvement of HEALS without the overhead of user-side software upgrading.

Current implementation of HEALS is a hybrid product of numerous development tools and applications. For the sake of controlling the budget and the pursuit of the Open Source Community, most of HEALS are implemented on open source software [24]. The core programs of HEALS are written mainly in PHP. The database connectivity layer is built with Java technologies and extensible markup language (XML) for their versatilities in distributed programming. The Apache HTTP server gives a highly available Web platform. The Apache Jakarta Tomcat server works for Java web-services. The Linux operating system is adopted due to its free cost and advantages in server programming without omitting functionality.

PHP is a widely used open source general purpose scripting language that is especially suited for Web development and can be embedded into HTML. Its syntax draws upon C, Java, and Perl, and is easy to learn [25]. The

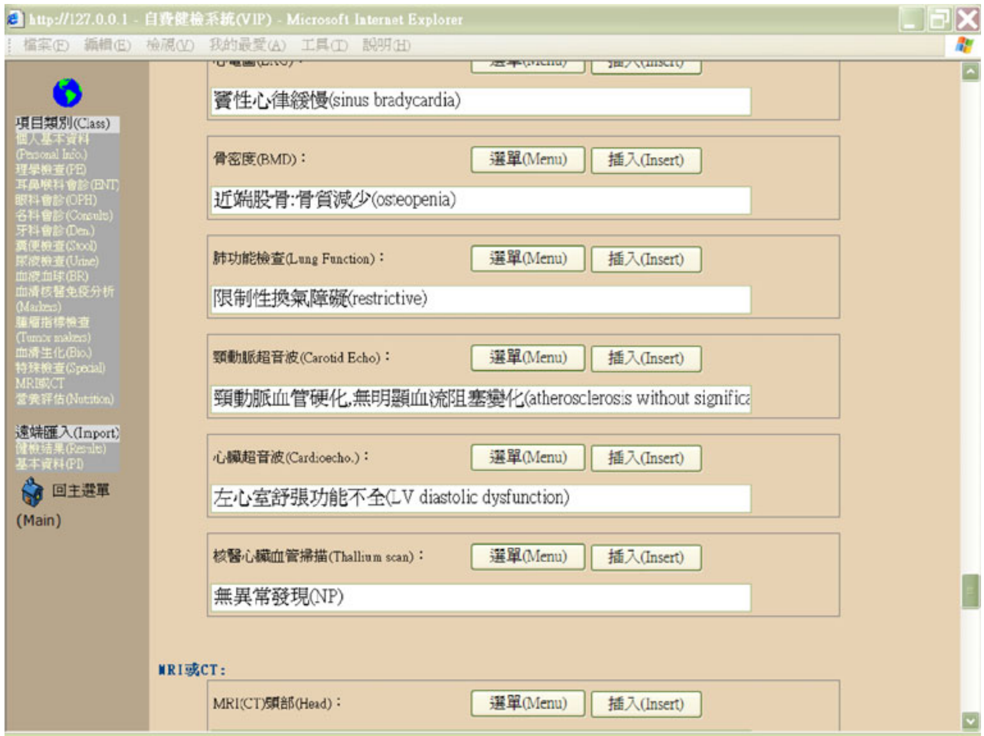

Fig. 4 Screen shot of HEALS. Editing the text fields

Java programming language is a high-level language that can be characterized by the following: simple, architecture neutral, object oriented, portable, distributed, high performance, multithreaded, robust, dynamic, and secure [26]. The XML is a simple, very flexible text formatting language. The XML plays an increasingly important role in the exchange of a wide variety of data on the Web and elsewhere [27]. The Apache is an open-source HTTP server

Fig. 5 Screen shot of HEALS. Editing the summary, which is the output of automated inference

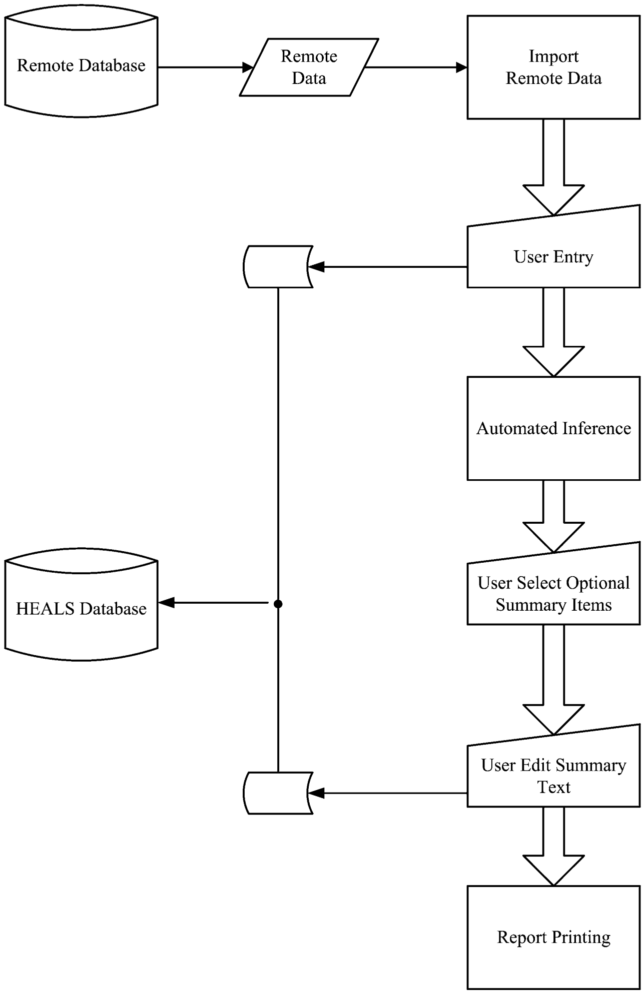

Fig. 6 Workflow of HEALS. Remote database is the repository of laboratory test results and administrative data. Most hospital information systems can provide above database. User Entry stage can let users check the correctness of imported data and manually edit the fields. After the Automated Inference stage, some undetermined abnormal items are kept for user judgments and selections. The summary text will be generated based on above automated inference output and user selection. Users can edit the summary text followed by printing reports. A local database of HEALS stores all related data

for modern operating systems including UNIX and Windows NT. The Apache HTTP server has been the most popular web server on the Internet [28]. The Apache Jakarta Tomcat server is the official reference implementation container for the Java Servlet and JavaServer Pages technologies [29]. The Linux is a free Unix-type operating system originally created by Linus Torvalds with the assistance of developers around the world [30].

The most important point of HEALS architecture is its platform independency. We intend to use development tools and technologies that are available on multiple platforms, at least on Linux and Microsoft Windows.

Evaluation and results

Evaluation of quality

The workflow of HEALS is illustrated in Fig. 6. We put the quality issue as the first evaluation topic because the guarantee of quality reports is the most important goal of the design of HEALS. Validation of the health reports is an essential issue that determines the quality of health reports and the confidence of the health examination customers. Automated inference outputs, which contain diagnoses and recommendations generated by the HEALS CDSS, are the source of evaluation for quality. In the daily operation of HEALS, experienced physicians take responsibility for rechecking the health reports and, if necessary, making appropriate edits to the contents of automated inference output. Automated inference outputs have three conditions in this rechecking and editing process (Table 1). In Table 1, the first case of the automated inference output is adequate and undemanding of user editing. The second case needs user editing to combine the abnormal health examination results from two groups into one group. The third case needs user editing for the recommendation content generated by automated inference. These three conditions are regarded as correct inference outputs. In contrast, any suspected error about automated inference will be quickly reported to the system administrator by the experienced physicians who are responsible with rechecking the reports. The system administrator reviews these reported possible errors and classifies them into four classes: major system error, minor system error, user error, and improvement comment (Table 2). The first two classes of errors are due to errors of automated inference. The third class of errors comes from user issue, such as input errors or unfamiliarity with the system. Users' constructive suggestions belong to the improvement comment class. To monitor the first two classes of errors can reveal the automated inference errors detected by physicians, which is closely related with the quality of automated inference. Our statistical data (Table 3) of the user reported possible errors for automated inference reveal no major or minor system error in 14,773 cases of health examination during 6 months of operation.

Both the evaluation of automated inference validity and refinement of the content base of HEALS are integrated into the workflow in daily practice. Valid automated inference outputs not only improve the quality of reports but also reduce the workload for physicians. The fact that users benefit from the automated inference validity improvement encourages voluntary user feedback. This positive cycle keeps the system vigorous.

Table 1 Examples of the contents of automated inference output before and after user editing

	Before	After
1	Positive hepatitis B surface antigen	Positive hepatitis B surface antigen
	Abnormal liver function tests	Abnormal liver function tests
	Abdominal echo: Moderate fatty liver. Diffuse liver disease	Abdominal echo: Moderate fatty liver. Diffuse liver disease
	Don't take medication without a physician's instructions, so as to avoid augmenting the workload of liver	Don't take medication without a physician's instructions, so as to avoid augmenting the workload of liver
	Take a rest, as appropriate; avoid being physically and mentally exhausted	Take a rest, as appropriate; avoid being physically and mentally exhausted
	Take exercise regularly	Take exercise regularly
	You are a hepatitis B carrier. Please have a follow-up consultation in the Outpatient Clinic of Division of Family Medicine every half an year	You are a hepatitis B carrier. Please have a follow-up consultation in the Outpatient Clinic of Division of Family Medicine every half an year
2	Elevated eosinophil	Elevated eosinophil
	No medical treatment is required, as the disorder is caused by an allergy Please have a follow-up consultation in the Outpatient Clinic of Division of Family Medicine in 6 months	Nose: allergic rhinitis Please visit the Outpatient Clinic of Division of ENT for a follow-up diagnosis and treatment, in the event of prolonged discomfort, such as a stuffy nose, a running nose or throat discomfort
	Nose: allergic rhinitis	
	Please visit the Outpatient Clinic of Division of ENT for a follow-up diagnosis and treatment, in the event of prolonged discomfort, such as a stuffy nose, a running nose or throat discomfort	
3	UGI image study: GERD. Gastric erosion	UGI image study: GERD. Gastric erosion
	Avoid coffee, chocolate, mint, sweet foods and greasy foods	Avoid coffee, chocolate, mint, sweet foods and greasy foods
	Use a relatively thick pillow.	Use a relatively thick pillow
	Avoid smoking and second-hand smoking	Avoid smoking and second-hand smoking
	Don't drink and eat too much at one meal; and avoid eating any food that may cause discomfort to the stomach	Don't drink and eat too much at one meal; and avoid eating any food that may cause discomfort to the stomach
	Please visit the Outpatient Clinic of Division of Gastroenterology Medicine for a follow-up diagnosis and treatment, in the event of a sense of "post-sternal burning", chest pain or acid regurgitation	Please visit the Outpatient Clinic of Division of Gastroenterology Medicine for a follow-up diagnosis and treatment in 3 months

The first example is the case that the automated inference output is undemanding of user editing. The second example is the case that needs user editing to combine the abnormal health examination results from two groups into one group. The third example is the case that need user editing for the recommendation content generated by automated inference

Evaluation of effectiveness

The effectiveness of HEALS is determined by whether physicians actually get assistance from HEALS. Since the most highlighted character of HEALS is its CDSS, we focus on studying the contribution provided by CDSS when physicians work with HEALS. The summary text of a health report contains diagnoses and recommendations. Without the assistance of HEALS, physicians have to gather related clinical data and write a proper summary text by themselves. Imperfection or mistakes in human-made summary text are unpreventable due to individual variations in medical knowledge, ability to express oneself, operating fatigue, and other internal or external conditions. We expect summary texts from the automated inference outputs of HEALS CDSS would eliminate such negative effects in report quality and thus provide positive support to physicians.

We designed a test with questions and asked common clinical problems originating from our health examination database and within the knowledge domain of HEALS CDSS. These questions can evaluate testers' summary text generation abilities, which require multi-domain skills such as medical, social, and communication fields. We invited eight participants who are residents of Taipei City Hospital with less than 2 years of clinical experience. With the test results, we compared the summary text generation abilities between human participants and HEALS. This comparison demonstrates whether HEALS CDSS is effective.

Table 2 Four classes of possible user-reported errors during rechecking the automated inference outputs

Major system error
1. Unable to inference for abnormal health examination results
2. Wrong inference for abnormal health examination results
Minor system error
1. Wrong grouping for abnormal health examination results
2. Insufficient recommendation for abnormal health examination results
3. Inaccurate recommendation for abnormal health examination results
User error
1. Input missing
2. Wrong input data type
3. Wrong input data
Improvement comment
1. Improvement for input
2. Grouping for abnormal health examination results
3. Improvement of the recommendation for abnormal health examination results

First, we must have golden standard answers for these questions. In our method, these answers were judged by two senior physicians with more than 10 years experience in health examination. Second, with these questions as input, we executed the automated inference process of HEALS and compared the inference outputs with the standards. This step is used to confirm the automated inference process of HEALS CDSS before the test. Eventually, the automated inference outputs are identical with the gold standard answers. Third, the participants were tested. Every question had four to seven answer options. These options were divided into three levels of correctness—completely correct, partially correct, and least correct. For each question, only one or two answers are qualified as completely correct and the others are qualified as partially correct or least correct. This division is designed to reduce the experimental bias due to inevitable medical uncertainty. However, it is difficult to make an absolute, correct medical decision with limited clinical information.

The experimental results show a significant variance for research participants among different questions (Table 4). Over 70% of answers are qualified as completely or partially correct (C + P) in eight of the 11 questions. Questions 3 and 6 get only 50% of C + P answers. Question 3 (Fig. 7) asks the thinking process for diagnosing hepatitis B, which is a specific topic for novice doctors. Question 6 (Fig. 8) requests research participants to give a diagnosis from limited laboratory results. Eighty-two percents of the answers qualified as completely or partially correct (C + P) in the 11 questions. Eighteen percent of the answers qualified as least correct. Equivalently, the testers would get at least 18% improvement in solving these test cases under the assistance of HEALS CDSS.

Evaluation of system performance

System performance measurement includes only the time used solely for of automated summary text generation, which completely avoids the influence of human. This measurement excludes the parts of HEALS which need human-machine interaction. The automated report generation procedure includes interpreting and executing the decision rules, code table mapping, and text formatting. For the same task, physicians need to gather necessary clinical data, interpret the data, make diagnoses, give appropriate recommendation, and edit the final report.

Table 3 Statistical results of the four classes of possible user-reported errors for automated inference during 6 months of operation of HEALS

	2007						
	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Major system error	0	0	0	0	0	0	0
Minor system error	0	0	0	0	0	0	0
User error	5	2	32	3	1	1	44
Improvement comment	0	0	2	2	3	3	10
Total case number of health examination	1,913	716	10,163	811	491	679	14,773

Table 4 Numbers of answers of three different correctness degrees

	Question no.										
	1	2	3	4	5	6	7	8	9	10	11
Complete (C)	1	7	2	8	1	4	5	6	5	3	5
Partial (P)	6	1	2	0	7	0	2	0	3	3	1
Least (L)	1	0	4	0	0	4	1	2	0	2	2
Ratio of C + P	0.875	1.000	0.500	1.000	1.000	0.500	0.875	0.750	1.000	0.750	0.750
Ratio of L	0.125	0.000	0.500	0.000	0.000	0.500	0.125	0.250	0.000	0.250	0.250

Ratio of completely and partially correct answers. Ratio of least correct answers

Performance of HEALS CDSS automatic summary text generation is measured during daily operation. The consistency of less than one second fulfils our expectation.

Evaluation of efficiency

The system operating time required to complete health reports is selected as the measurement of the system efficiency of HEALS. The measured time starts with the data entry and ends at report printing. Three parts of the time measurement are: time to edit the entry fields, time to select optional summary items, and time to edit the summary text. In a fully loaded environment, throughput of health reports is markedly influenced by the system operating time to complete health reports. The evaluation results of efficiency are summarized in Table 5.

About fifty input entry fields need to be edited in the simplest health examination package. The most complicated health examination package consists of more than two hundred input entry fields. Physicians need to input, check, or edit these fields. In evaluating the time to edit the entry fields of each report, the most common is 1 to 3 min. Of 5,108 cases, 4,405 (86.24%) are within 5 min (Fig. 9).

After automated inference by HEALS CDSS, output is generated and some optional summary items are displayed for user selection. The time used to select optional summary items is the least of all types in this evaluation. As the inference power of HEALS CDSS improves, fewer optional summary items need to be selected. Of 3,888 cases, 3,202 (82.36%) are within 1 min, and 2,360 cases (60.70%) are within 10 s (Fig. 10).

Summary text editing is the final step requiring human intervention. It contains the text generated by HEALS CDSS automated inference and optionally selected summary items. With the aid of HEALS CDSS, summary text should need only minor editing. In evaluating the time to edit the summary text of a report, we find that 3,494 of 4,356 (80.21%) cases take less than 3 min each. Notably, more than 60% of the cases (2,641/4,356) take less than half a minute each (Fig. 11).

Summation of these three measurements reveals most cases fall in the interval of 60 to 300 s. Among 4,672 cases, 4,404 (94.26%) take less than 10 min and 3,831 of 4,672

1. HBsAg: negative, Anti-HBs: negative, Anti-HBc total: positive
Please make a diagnosis.
a. Indicate immunity to HBV
b. Indicate chronic HBV infection
c. Indicate acute HBV infection

3. Follow Question 1. What related information you may need for a more definite diagnosis?
a. Previous test result of HBsAg
b. Previous test result of Anti-HBs
c. Previous test result of Anti-HBc
d. Previous test result of liver enzymes

Fig. 7 Questions 1 and 3 are designed for testing the thinking process for diagnosing hepatitis B. The answer of Question 1 is a or b. In Question 3, for a more definite diagnosis, previous test results of HBsAg and Anti-HBs are necessary

4. RBC: $4.8*10^6$/uL, MCV: 63fL, Hemoglobin: 10.5g/dL
Please make a diagnosis.
(uL: microliter, fL: femtoliter, dL: deciliter)

a. Microcytic anemia
b. Suspected thalassemia
c. Suspected thalassemia carrier
d. Suspected iron deficiency anemia
e. Suspected chronic disease induced anemia

6. Follow Question 4. The patient is a female. Ferritin: 13ng/mL.
Please make the most appropriate diagnosis.
a. Microcytic anemia
b. Suspected thalassemia
c. Suspected thalassemia carrier
d. Iron deficiency anemia
e. Suspected chronic disease induced anemia

Fig. 8 Questions 4 and 6 are designed for testing the thinking process for diagnosing anemia. Regarding the provided laboratory data in Question 4, red blood cell count, mean corpuscular volume, and hemoglobin, microcytic anemia is the most appropriate diagnosis since the criteria of other diagnoses are not fully fitted. In Question 6, 13 ng/mL of ferritin in a female patient still cannot be confirmed as iron deficiency

Table 5 Summary of the evaluation results of efficiency of HEALS

Time interval (s)	Total (s)	Edit (s)	Summary select (s)	Summary edit (s)
<10	12	398	2,360	1,824
10–30	286	1,027	623	817
30–60	625	932	219	431
60–180	2,077	1,470	137	422
180–300	831	578	57	186
300–600	573	495	112	235
600–900	149	119	56	142
900–1,800	101	77	91	177
1,800–3,600	15	11	111	64
≥3,600	3	1	122	58

The unit is second

(82.00%) cases take less than 5 min (Fig. 12). In contrast with the amount of time with the computer assistance of HEALS, a physician needs at least 20 min to accomplish above jobs for a complex health examination case manually. The improvement of efficiency in report generation is significant with the assistance of HEALS.

Discussions

We have reviewed literature in order to compare with our proposed system. Nevertheless, articles relate with CDSS for health examinations are absent in our knowledge. However, there are still CDSS studies for different medical fields proposed and evaluated.

Several rule-based medical expert systems based on Lhostska's FEL-EXPERT shell [31] including MYOPAT, METABOL-AC, application in oncopathology, and FEL-MOT are evaluated on typical examples of individual diseases only. In these four systems, nearly 100% correspondence with medical doctor's diagnosis was reached. MYPOT is an expert system for diagnosing three genetic syndromes. METABOL-AC was constructed to solve the diagnosis of inherited metabolic disorders. FELMOT is a diagnostic system for vestibular organ disorders. Another application is made for oncopathology.

Achour et al. constructed a CDSS that assists in the blood transfusion at the Henri Mondor Hospital in Creteil, France [32]. The system works according to the data-driven and application-driven principles of the MLM of the Arden Syntax. The evaluation was performed to validate the coherence and the correctness of the CDSS. Some disagreements occurred between physician's orders and CDSS conclusions, but agreement between the CDSS and the experts who reviewed the orders was 100%. Achour et al. argue that their approach is a practical way to build CDSSs.

Saade et al. developed a web-based decision support system called OSTEODSS and integrated into the clinical workflow for generating the reports of osteoporosis management [33]. The system was evaluated by ten general practitioners. The main feedback obtained includes: nine out of the ten general practitioners agreed that the report was of high quality and accurate; the use of the system would save time; all general practitioners were not confident in identifying whether the report is machine or specialist generated.

Huang et al. proposed a web-based Chinese Medical Diagnostic System (CMDS) for digestive health [34]. To

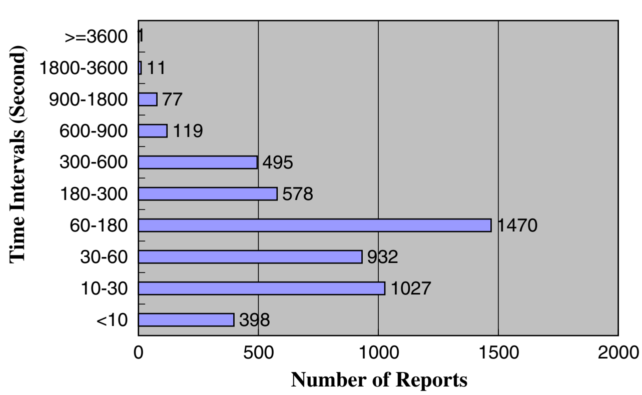

Fig. 9 Time to edit the entry fields of a report. Detailed description in Section Evaluation of Efficiency

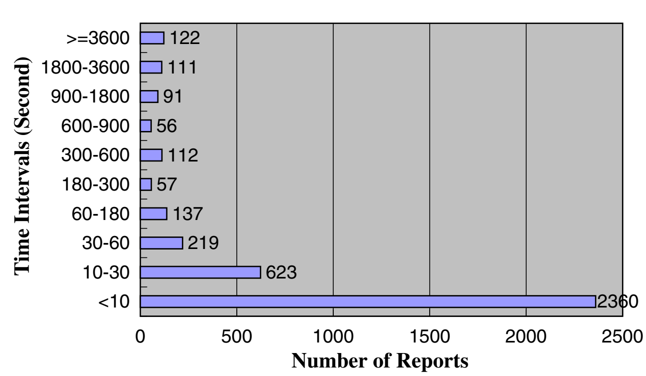

Fig. 10 Time to select optional summary items of a report. Detailed description in Section Evaluation of Efficiency

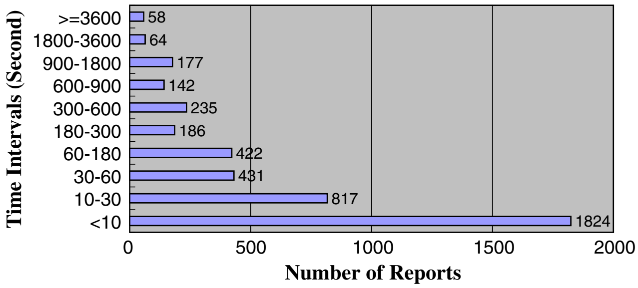

Fig. 11 Time to edit summary text of a report. Detailed description in Section Evaluation of Efficiency

evaluate the system, simulation with some cases was performed. The results were obtained from the diagnosticians and the CMDS independently and that revealed almost identical answers.

Comparing the CDSS output result with experts' opinions is the common evaluation principle used for these systems. This is identical with the evaluation of quality of our proposed system in Section Evaluation of Quality. HEALS CDSS has reached the stable stage of 100% correct automated inference output. The "save time" issue is also addressed in Section Evaluation of Efficiency. Although we cannot find similar system to make direct comparison in "time" issue, the senior clinicians show the efficiency of HEALS CDSS by comparing between the amount of time with and without HEALS. The improvement of efficiency in report generation is significant with the assistance of HEALS.

The flexibility of the architecture of HEALS is an advantage that can be easily extended to work for different health examinations. HEALS effectively produces a sophisticated health report, increases the satisfaction of both professionals and customers, and potentially plays an important role in resident doctors training.

DeLone and McLean introduced six dimensions of success in management information systems [35]. In the review by Meijden et al., the same success dimensions are also valid for healthcare information systems [36]. The six categories of success in information systems are system quality, information quality, use, user satisfaction, individual impact, and organizational impact. One of the major reasons for the success of HEALS is that the developers of the system are also users. At least the first four categories of success for information systems are easily achieved because the users are also the developers. In such a circumstance, all of the practical requirement derived from users can be quickly implemented into HEALS. This is the major advantage contributing to the success of HEALS.

We identify four classes of common errors in health reports: (1) failure to correctly detect problems from multiple examination results; (2) failure to give proper recommendations for further medical management or life style modification; (3) failure to write a well-edited report; and (4) failure to meet the deadline for delivering reports.

A health examination will produce a large amount of clinical data that needs a sophisticated interpretation to get the most appropriate diagnosis and recommendations. For example, detailed liver examinations may include alanine aminotransferase, aspartate aminotransferase, gamma-glutamyltransferase, total protein, albumin, viral hepatitis markers, alpha-fetoprotein, and abdominal ultrasound. Physicians should consider all available clinical data to make proper decisions. Unfortunately, humans do make errors [37]. The chance of an error increases in proportion to the complexity of the examination. However, any error in interpreting health examination data risks causing mistakes in health care and, thus, patient safety. There are two kinds of mistakes in health reports, false negatives and false positives. Even a tiny mistake in the health report may cause false negatives or false positives. False negative reports hide potential disorders of the patient. In the worst case, the patient risks delayed diagnosis and treatment. The hospital or clinic and physicians may face legal and ethical liabilities. False positive reports give arbitrary or excessive diagnoses to an unaffected person. The effects of false positives include unnecessary anxiety of the patients, further unnecessary medical diagnostics, and unnecessary and potentially harmful intervention. HEALS resolves the problems of potential human errors in interpreting health examination data by the powerful automated inference ability in its CDSS.

In making recommendations for a diagnosis attention needs to be given to the severity of the disorder, the general condition of the patient, and the individual's external environment. All of these are judgment calls by the physician, and different physicians may give different recommendation for the same clinical condition. Also, a physician may even give different recommendations for the same clinical condi-

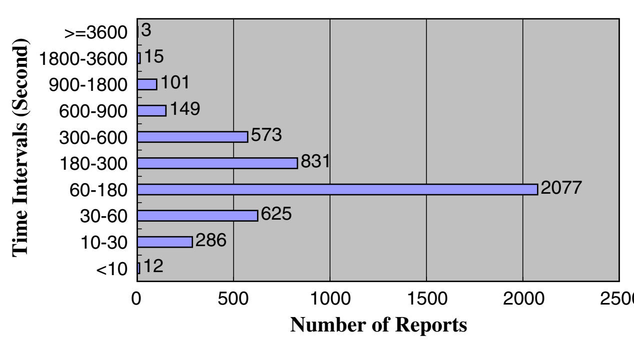

Fig. 12 Time to complete a health report (the total of time to edit the entry fields, time to select optional summary items, and time to edit summary text). Detailed description in Section Evaluation of Efficiency

tion at different times. The automated inference of HEALS CDSS outputs not only the health problems found in health examination results but also recommendations related to above health disorders for the patients.

Clinical conditions and recommendations should be translated into comprehensive text which can be understood by patient to prevent misunderstanding of the reports [38]. To provide assistance to alleviate the language gap between health examination customers and physicians, the knowledge base of HEALS CDSS contains plenary content that can be assembled to a comprehensive text after the automated inference for health examination results.

Furthermore, a good health report should be produced in a timely manner. The promptness of health reports is also a crucial issue for customer satisfaction. HEALS provides a solution to generate health reports in a quality and efficient way. A quality health report prevents repeated revising thus significantly reduces the time needed for finalizing.

Conclusion

In this paper, we have shown the development and evaluation for a clinical decision support system used in health examinations. Our main innovations are: (1) to construct an evolutional knowledge-based system to fundamentally improve the work flow of health examinations; (2) to evaluate a CDSS in a multi-facet way.

We have presented a web-based system for health examinations named HEALS. HEALS serves mainly as an assistant in the daily work of health examinations. The evaluation of effectiveness also proves HEALS has an education role. To maximize the power of HEALS CDSS, a novel rule syntax is proposed to construct the knowledge base of CDSS. The success of HEALS has shown the capability of the rule syntax.

HEALS aims to facilitate the workflow of health examinations and eliminate four classes of failure. Implementing a health examination information system will improve the availability, efficiency, and quality of health care management. HEALS is under continuous development to achieve improvement, and we anticipate implementing broader applications in HEALS. Future plans for evolution include: (1) to incorporate different artificial intelligence technologies, such as case-based reasoning, neural network, and so on; (2) to evaluate more aspects to explore future direction of HEALS and improve the total quality of health examinations.

Acknowledgements The authors would like to thank for the assistance of colleagues at RenAi Branch, Taipei City Hospital.

Reference

1. Fitzmaurice, J. M., Adams, K., and Eisenberg, J. M., Three decades of research on computer applications in health care medical informatics support at the agency for healthcare research and quality. *J. Am. Med. Inform. Assoc.* 9:144–160, 2002. doi:10.1197/jamia.M0867.
2. Fuh, C. S., and Kuo, K. L., The decision support system used in HEALS (Health Examination Automatic Logic System). *2006 American Medical Informatics Association Spring Congress Poster*. May 16–18, 2006.
3. Kuo, K. L., and Fuh, C. S., HEALS: Health Examination Automatic Logic System. *2006 American Medical Informatics Association Spring Congress Poster*. May 16–18, 2006.
4. Canadian Task Force on Preventive Health Care, Evidence-based clinical prevention. 2000.
5. Canadian Task Force on the Periodic Health Examination: Periodic health examination monograph: report of the Task Force to the Conference of Deputy Ministers of Health. 1980.
6. Agency for Healthcare Research and Quality, Guide to Clinical Preventive Services, 2006: Recommendations of the U.S. Preventive Services Task Force. *AHRQ Publication No. 05-0570*. 2006.
7. Ohno-Machado, L., Gennari, J. H., Murphy, S. N., et al., The GuideLine interchange format: a model for representing guidelines. *J. Am. Med. Inform. Assoc.* 5:357–372, 1998.
8. Wang, D., Peleg, M., Tu, S. W., et al., Representation primitives, process models and patient data in computer-interpretable clinical practice guidelines: a literature review of guideline representation models. *Int. J. Med. Inform.* 68:59–70, 2002. doi:10.1016/S1386-5056(02)00065-5.
9. Bennett, J. W., and Glasziou, P. P., Computerised reminders and feedback in medication management: a systematic review of randomised controlled trials. *Med. J. Aust.* 178:217–222, 2003.
10. Casalino, L., Gillies, R. R., Shortell, S. M., et al., External incentives, information technology, and organized processes to improve health care quality for patients with chronic diseases. *JAMA*. 289:434–441, 2003. doi:10.1001/jama.289.4.434.
11. Chaudhry, B., Wang, J., Wu, S., et al., Systematic review: impact of health information technology on quality, efficiency, and costs of medical care. *Ann. Intern. Med.* 144:742–770, 2006.
12. Jiang, S. T., How information technologies have improved both productivity and quality of health care. *J. Med. Eng. Technol.* 29:38–41, 2005. doi:10.1080/03091900412331271130.
13. Nobel, J., Bridging the knowledge-action gap in diabetes: information technologies, physician incentives and consumer incentives converge. *Chronic Illn.* 2:59–60, 2006.
14. Sequist, T. D., Cullen, T., and Ayanian, J. Z., Information technology as a tool to improve the quality of American Indian health care. *Am. J. Public Health*. 95:2173–2179, 2005. doi:10.2105/AJPH.2004.052985.
15. Sim, I., Gorman, P., Greenes, R. A., et al., Clinical decision support systems for the practice of evidence-based medicine. *J. Am. Med. Inform. Assoc.* 8:527–534, 2001.
16. Evans, R. S., Pestotnik, S. L., Classen, D. C., et al., A computer-assisted management program for antibiotics and other antiinfective agents. *N. Engl. J. Med.* 338:232–238, 1998. doi:10.1056/NEJM199801223380406.
17. Hunt, D. L., Haynes, R. B., Hanna, S. E., et al., Effects of computer-based clinical decision support systems on physician performance and patient outcomes a systematic review. *JAMA*. 280:1339–1346, 1998. doi:10.1001/jama.280.15.1339.
18. Johnston, M. E., Langton, K. B., Haynes, R. B., et al., Effects of computer-based clinical decision support systems on clinician

performance and patient outcome: a critical appraisal of research. *Ann. Intern. Med.* 120:135–142, 1994.

19. Osheroff, J. A., Teich, J. M., Middleton, B., et al., A roadmap for national action on clinical decision support. *J. Am. Med. Inform. Assoc.* 14:141–145, 2007. doi:10.1197/jamia.M2334.
20. Teich, J. M., Osheroff, J. A., Pifer, E. A., et al., Clinical decision support in electronic prescribing: recommendations and an action plan report of the joint clinical decision support workgroup. *J. Am. Med. Inform. Assoc.* 12:365–376, 2005. doi:10.1197/jamia.M1822.
21. Rector, A. L., Thesauri and formal classifications: terminologies for people and machines. *Methods Inf. Med.* 37:501–509, 1998.
22. Rosenbloom, S. T., Miller, R. A., Johnson, K. B., et al., Interface terminologies: facilitating direct entry of clinical data into electronic health record systems. *J. Am. Med. Inform. Assoc.* 13L:277–288, 2006. doi:10.1197/jamia.M1957.
23. Russell, S. J., and Norvig, P., *Artificial intelligence: a modern approach*, 2nd edition. Prentice Hall, Englewood Cliffs, NJ, New Jersey, 2003.
24. Kantor, G. S., Wilson, W. D., and Midgley, A., Open-source software and the primary care EMR. *J. Am. Med. Informat. Assoc.* 10:616, 2003.
25. The, P.H.P.: Group, PHP: Hypertext Preprocessor. [cited on Dec. 27, 2008]. Available from: http://www.php.net/.
26. Sun Microsystems, Inc.: About the Java Technology. [cited on Dec. 27, 2008]. Available from: http://java.sun.com/docs/books/tutorial/getStarted/intro/definition.html.
27. W3C, Extensible Markup Language (XML). [cited on Dec. 27, 2008]. Available from: http://www.w3.org/XML/.
28. The Apache Software Foundation, The Apache HTTP Server Project.: [cited on Dec. 27, 2008]. Available from: http://httpd.apache.org/.
29. The Apache Software Foundation: Apache Tomcat. [cited on Dec. 27, 2008]. Available from: http://tomcat.apache.org/.
30. Linux Online, Inc.: What is Linux. [cited on Dec. 27, 2008]. Available from: http://www.linux.org/info/index.html.
31. Lhotska, L., Marik, V., and Vlcek, T., Medical applications of enhanced rule-based expert systems. *Int. J. Med. Inform.* 63:61–75, 2001. doi:10.1016/S1386-5056(01)00172-1.
32. Achour, S., Dojat, M., Rieux, C., et al., A UMLS-based knowledge acquisition tool for rule-based clinical decision support system development. *J. Am. Med. Inform. Assoc.* 8:351–360, 2001.
33. Saade, R., Tsoukas, A., and Tsoukas, G., Prototyping a decision support system in the clinical environment: assessment of patients with osteoporosis OSTEODSS. *Expert Syst. Appl.* 27:427–438, 2004. doi:10.1016/j.eswa.2004.05.019.
34. Huang, M., and Chen, M., Integrated design of the intelligent web-based Chinese Medical Diagnostic System (CMDS)—systematic development for digestive health. *Expert Syst. Appl.* 32:658–673, 2007. doi:10.1016/j.eswa.2006.01.037.
35. DeLone, W. H., and McLean, E. R., Information systems success: the quest for the dependent variable. *Inf. Syst. Res.* 3:60–95, 1992. doi:10.1287/isre.3.1.60.
36. Meijden, M. J. v. d., Tange, H. J., Troost, J., et al., Determinants of success of inpatient clinical information systems: a literature review. *J. Am. Med. Inform. Assoc.* 10:235–243, 2003. doi:10.1197/jamia.M1094.
37. Balas, E. A., Information systems can prevent errors and improve quality. *J. Am. Med. Inform. Assoc.* 8:398–399, 2001.
38. McRoy, S. W., and Hirst, G., Misunderstanding and the negotiation of meaning. *Knowl.-Based Syst.* 8:126–134, 1995. doi:10.1016/0950-7051(95)98374-F.