First the Electrocardiogram—Then What?

A System for Decision-Making by Computer

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Electrocardiography has been the proving ground for many of the basic concepts of medical decision-making by computer. This paper describes a system in which these concepts have been generalized for application to the whole field of medical practice.

The HELP system[1] of computerized medical decision-making has been designed to provide the physician with processed information that will assist him in his role as decision-maker. When a system that has access to current medical knowledge in the form of criteria for making deductions and drawing conclusions from observations is coupled to a file containing data on a patient, it can go beyond the task of retrieving and reformatting data. It can help the physician make appropriate diagnostic, prognostic and therapeutic decisions. Decision-making represents the primary role of the physician, and he must bring to this task an ever-growing body of medical knowledge. This rapid increase in new medical knowledge has led to increasing specialization on the one hand and frustration of the generalist on the other. The HELP system is designed to provide consultation based on current medical knowledge to the specialist caring for a patient who has problems outside his special area of expertise and to the generalist who is faced with a problem he may not recognize or a situation in which he lacks experience. Because the system reacts automatically to each new data entry by examining new data in the context of all pertinent previous data on this patient according to rules specified by the medical logic stored in the form of decision criteria, the appropriate medical knowledge will always be promptly brought to bear on each patient's problem. When new knowledge is acquired an additional modification can easily be made to the appropriate component of the system and that new knowledge will automatically be applied to the solution of each patient's problem from that moment on.

Design of HELP System

The basic design considerations of the HELP system and the hypotheses upon which these design features are predicated are shown below.

1. Because experience both in our hospital and elsewhere has shown that it is difficult to entice a physician to enter information into a computer, the HELP system is designed to acquire most of its information about a patient automatically or through paramedical persons. It is designed to make the physician the recipient of information primarily and only in special instances the provider of data.

2. Because the most common type of decision error in medicine is the result of a failure to consider the proper decision, the HELP system is designed to be data-driven. This means that each time a new item of information is added to a patient's file any decisions that make use of that information are automatically processed at that time.

3. Because decision logic is not static over time but changes as new medical knowledge is acquired, logic in the HELP system is stored independently of the computer program that executes it. As new medical knowledge becomes available the decision criteria can be modified without changing any programs in the computer. A common program processes all medical logic and only this common program need be implemented on another computer in order to transfer the medical ware directly.

4. Because the decisions made by the HELP system are to be used in the actual care of patients it is necessary that a physician be responsible for the logic behind each decision. For this reason HELP decisions are expressed in natural language so that a medical expert with no computer experience can generate the logic with enough confidence to assume responsibility for the decisions the computer makes. The decision logic is therefore self-explanatory, which again facilitates transfer of logic developed at one institution to another setting.

5. Because the system is data-driven, the logic for at least one decision is processed almost any time an item of information is entered into any patient's file. It is important, then, that this logic be processed efficiently in order to keep computing costs at a minimum. To accomplish this the natural language source statements representing the medical logic are converted to a tightly coded form ready for efficient processing before they are stored on disc for use by the system. Much effort has gone into this kind of optimization.

6. Because simple approximations to the real logic used by an expert in making subtle decisions will not be accepted in the real world of patient care, the HELP system has been designed to allow the user not only to use sophisticated logical and probabilistic expressions but also to specify complex relations in time sequences among the data required to make a decision. The system, in addition, is hierarchical in order that some decisions may be based on other decisions as well as on raw data to any level desired.

7. Because a very large number of possible decisions might be incorporated in such a system, HELP is designed to be modular so that it can start performing a useful service even with a small subset of its eventual complement of decision logic. This modularity also facilitates division of responsibility for the system logic among experts, each one managing the decisions in his area of expertise. Without this, maintenance of a system with this complexity would become overwhelming.

8. With the rapid advance of medical science, the opinions of experts today may not be considered the best basis for de-

cisions of tomorrow. The HELP system has been designed to provide much of the information needed to improve upon its current decision logic. Thus, there is reason to believe that although decisions made by HELP at the outset are no better than the logic provided by the experts, the system itself can provide data that will form a basis for improved logic in the future.

Source of Data for Decision-Making System

The HELP system incorporating these features has been implemented at the LDS Hospital in Salt Lake City. This is a 550 bed general hospital manned almost exclusively by a staff of 290 specialists in private practice. Of the 150,000 patient records currently in the system, 4,000 are maintained on the active patient disc at all times.

The sources of data for the decision-making system are the following:

1. Each patient on elective admission to the hospital takes a self-administered history while sitting at a terminal.[2] From the answers to these questions HELP decisions are processed on the basis of conditional probabilities to provide the attending physician with a list of suggested diagnoses and the reasons for these suggestions. This procedure and the other components of the screening process are designed to detect secondary problems that may alter patient management because most patients whose physicians use the HELP system are coming into the hospital for elective surgery.

2. *An electrocardiogram* is obtained on each patient during the screening and processed on-line by the computer.[3] The variables extracted by the electrocardiographic program and stored in the patient record are interpreted by the HELP system, both from screening and from signals transmitted from the patient's room over his telephone later in his hospital stay. Comparison of serial electrocardiograms is also made by the HELP system.[4]

3. *Spirometry* is also performed on-line as part of the screening operation. A report of these first three items of information is printed in the screening facility and taken to the ward with the patient.[5]

4. *In the pulmonary function laboratory* several more sophisticated breathing functions, as well as blood gas values, are measured using instruments connected on-line to the computer.[6] Processed data as well as interpretations based on HELP logic are fed back to the technician as part of the quality control process.

5. *In the exercise laboratory* three channels of electrocardiographic information are processed on request from the technician or monitoring cardiologist at various stages of exercise. Signal averaging after rejection of extrasystoles is employed to provide a clean signal for interpretation.[7]

6. *In the cardiovascular laboratory* all hemodynamic data are acquired on-line during the procedure.[8] Left ventricular angiograms are recorded on video disc and then processed by computer to determine left ventricular border coordinates for each frame during a cardiac cycle. A model based on the synchrony of border motion is used to detect areas of abnormal contraction.[9]

7. *The clinical laboratory,* including chemistry, hematology, microbiology and various special procedures, is on-line to a stand-alone laboratory computer system, which in turn interfaces to the HELP system. When these data are verified by each responsible technician, they are transmitted to the HELP system for storage in the patient file. This triggers the processing of any logic that uses that particular data item.

8. *Three files are maintained in the blood bank on each unit of blood*—a donor file, a unit file and a record in the file of the patient who receives the unit of blood.

9. *Every prescription sent to the pharmacy* is entered by the pharmacist through a terminal.[10] The computer prints labels, maintains a drug file for each patient and uses HELP to decide whether that prescription is potentially hazardous to the patient in light of his known sensitivities, other drugs he is taking, his kidney function or other variables that might be deduced from laboratory or other data in his file. If an alarm is generated the clinical pharmacist goes to the ward to bring this information to the attention of the responsible physician or nurse.

10. *Demographic information* obtained during the admitting process may be used for certain decisions.

11. *In the record room* additional information, including the discharge diagnosis, is abstracted from the patient's written chart.

12. *Thirty-one intensive care unit and coronary care unit* beds are monitored directly by the computer for a variety of hemodynamic and rhythm measurements and recordings.[11] Observations by the nurse are entered through the terminal in order to provide a computer record that contains all the information needed for patient care.

13. *Finally, there are terminals on all 31 nursing stations* which are used for entering certain types of information such as increased patient temperatures. However, these terminals are primarily used for reviewing patient data.

Modes of Decision Output to Physician

The decisions made by the HELP system and the data used for these decisions are available to the physician in three modes:

There are four types of routine reports upon which HELP decisions may appear. These include the reports from all of the laboratories, the admissions screening report, the 8 hour shift reports, the cumulative 5 day reports in the intensive and coronary care units and the printed gummed labels attached to the electrocardiograms placed in the chart. A physician may gain access to HELP decisions on his patients through a keyboard TV-type terminal in the doctors' lounge, at each nursing station or in any of the intensive care units. He does this by calling a program that asks him for his code number and then displays a list of patients who are his responsibility. The list of current decisions on any patient may then be examined, as well as the latest data from the sources just described. In addition, from the doctors' lounge or in the intensive care unit, he may obtain a hard copy printout of any of this information.

The third mode of decision output is represented by alerts to the clinical pharmacist in the case of potential adverse drug reactions to a prescription, to a nurse clinician for problems such as an increase in the patient's temperature or laboratory values that indicate several electrolyte disturbances that are not being managed appropriately. In the intensive care unit certain decisions may turn on a red light on the monitoring panel. When a nurse or resident presses that light switch a message describing the alert is displayed on the terminal. Finally, programs are operational that provide the chief of any service with the facility to follow the course of all patients in any category he describes by any logical combination of HELP decisions in the system.

For instance, the chief of pathology is now following up on a day to day basis all patients who have a hypochromic microcytic anemia but who have not undergone a serum iron and iron binding capacity tests.

Illustrative case examples: An example of a HELP sector designed to evaluate the probability that a patient taking the self-administered history has a hiatal hernia as the explanation for his symptoms will serve to illustrate one form decision logic may take in the HELP system (Table I). Items A thru G are variables, each represented by 2 bits in the patient's record. The first bit indicates whether the question was asked and the second whether it was answered "yes." On each question there are delimiters that specify that the last entry of this type of data from 1 month before now until now should be used. Items H thru M specify the parameters of the sequential Bayesean probability estimates to be performed on variables A thru G. The number 14 is the a priori probability expressed as 14 per 1,000 patients in this population being screened who have hiatal hernia. The next two numbers, 570 and 120, in the case of item H represent first the probability of getting a "yes" answer to question A—"Do you have pain made better by milk or antacids?" in patients with hiatal hernia, and the second number, 120, is the expressed frequency per 1,000 "yes" answers to this question given by patients who do not have hiatal hernia. The results of this calculation will become the value for item H and looking at item I item H is then used as the a priori probability in the next stage of the process.

Another type of decision format is shown in Table II. This type not only makes a decision, but also calculates a value that is inserted into the message displayed

TABLE I

A HELP Sector Used by the History Program to Determine the Probability That a Patient Has a Hiatal Hernia Based on His Answers to Each of the Questions Listed

```
SECTOR 3
HIATAL HERNIA (ESOPHAGITIS)
INHIBIT LOGIC = ALWAYS PRINT
*FVAL N
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*A          (A) DO YOU HAVE PAIN MADE BETTER BY MILK OR ANTACIDS. LAST FROM 1 MON BEFORE NOW
*B          (A) DO YOU GET BURNING PAIN IN THE CHEST OR ABDOMEN. LAST FROM 1 MON BEFORE NOW
*C          (A) HAVE YOU HAD CHEST PAIN MADE WORSE BY EATING OR DRINKING. LAST FROM 1 MON BEFORE NOW
*D          (A) DO YOU GET CHEST PAIN MADE WORSE BY LYING FLAT. LAST FROM 1 MON BEFORE NOW
*E          (A) DO YOU HAVE A LUMP IN THE THROAT OR DIFFICULTY SWALLOWING. LAST FROM 1 MON BEFORE NOW
*F          (A) HAVE YOU HAD RECURRING ATTACKS OF THE SAME CHEST PAIN. LAST FROM 1 MON BEFORE NOW
*G          (A) DOES BENDING OR STOOPING BRING ON PAIN OR MAKE IT WORSE. LAST FROM 1 MON BEFORE NOW
*H   PROB   TRIN  A  14   570   120
*I   PROB   TRIN  B  H    680   120
*J   PROB   TRIN  C  I    640    70
*K   PROB   TRIN  D  J    200    50
*L   PROB   TRIN  E  K    400    70
*M   PROB   TRIN  F  L    520   150
*N   PROB   TRIN  G  M    400   140
*O          IF (N LT 14), N = O EXIT
*P          IF (N LT 900) EXIT
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TABLE II

A HELP Sector That Alerts the Pharmacist If the Drug and Laboratory Values Stored in a Patient's Record Satisfy the Criteria Listed

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SECTOR 10
PATIENT IS RECEIVING POTASSIUM THERAPY BOTH IV AND ORALLY AMOUNTING TO A TOTAL OF = = MEQ DAILY, SUGGEST
DAILY MONITORING OF SERUM POTASSIUM.
INHIBIT LOGIC = 5
FVAL E
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A.     ELECTROLYTIC, CALORIC, AND WATER BALANCE AGENTS, (A) POTASSIUM REPLACEMENTS, (B) CURRENT, (C) IV, (D) DOSE,
       (E) INTERVAL BETWEEN DOSES (HRS) GET (D*24)/E LAST FROM 2 MON BEFORE NOW TO 24 HR BEFORE NOW
B.     ELECTROLYTIC, CALORIC, AND WATER BALANCE AGENTS, (A) POTASSIUM REPLACEMENTS, (B) CURRENT, (C) IV DRIP, (D)
       DOSE, (E) INTERVAL BETWEEN DOSES (HRS) GET (D*24)/E LAST FROM 2 MON BEFORE NOW TO 24 HR BEFORE NOW
C.     ELECTROLYTIC, CALORIC, AND WATER BALANCE AGENTS, (A) POTASSIUM REPLACEMENTS, (B) CURRENT, (C) ORAL, (D)
       DOSE, (E) INTERVAL BETWEEN DOSES (HRS) GET (D*24)/E LAST FROM 2 MON BEFORE NOW TO 24 HR BEFORE NOW
D. EX  IF (NOT ((A OR B) AND C)) EXIT
E.     A + B + C
F.     IF (E LT 60) EXIT
G.     (A) SMA-6 AND STAT ELECTROLYTES, K+ (X10 MEQ/L) BOOL A NE O LAST FROM 24 HRS BEFORE NOW
H.      EX IF G EXIT
I.     (A) SMA-6 AND STAT ELECTROLYTES, K+ (X10 MEQ/L) BOOL A NE O LAST FROM 48 HRS BEFORE NOW
J. EX  IF (NOT I) STOP
K.     IF (I LT 40) EXIT
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to the pharmacist. The top message indicates that the patient is receiving potassium therapy both intravenously and orally amounting to a total of_____ milliequivalents daily; daily monitoring of serum potassium is suggested. "Inhibit Logic = 5" simply states "Do not print this message if sector 5 is true." (Sector 5 decides if the patient already has hyperkalemia.) Item A prescribes a search of the patient's file for a data field indicating that he is currently receiving potassium replacements intravenously. The GET statement requests the dose (D) multiplied by 24 and divided by (E), the number of hours between doses. This will be the amount of potassium received by the patient in a 24 hour period and will become the value of item A. It will be taken from the *last* field in the time interval specified by 2 months before now and 24 hours before now. Items B and C are identical except for the route, which is, respectively, intravenous drip and oral. Item D is an exit statement that essentially says that if neither A nor B is found in addition to C, do not continue the calculation. Item E calculates the total dose of potassium received by all routes in a 24 hour period. Item F causes the program to exit if the total dose is less than 60 mEq/day. Item G searches for a serum potassium measurement in the last 24 hours and item I for a measurement sometime in the last 48 hours. If potassium has not been measured for 24 hours and the measurement the preceding day showed a value of more than 4 mEq/liter the sector is true, and a message suggesting monitoring for the potassium level will be printed.

STRATO Program

To facilitate the research needed to improve the decision logic of the HELP system a program called STRATO has been developed. With this system a user can create HELP sectors that can then be used to generate subpopulations that fill the criteria of these HELP sectors. For instance, subpopulation 1 might be those patients who had left ventricular angiograms performed before a bypass graft was placed in the anterior descending coronary artery and whose graft was patent 6 months postoperatively while subpopulation 2 filled the same criteria except that the grafts were not functional on follow-up study. A third sector may then be created to define a variable such as that describing left ventricular wall motion in the area supplied by the left anterior descending artery before surgery. The distribution of values for this variable can then be compared in patients from the two populations and the results used to define new decision logic for assisting the physician in choosing patients for this operation in the future.

Clinical Implications

What does the future hold for a system like HELP?

Public pressure is demanding quality assurance and cost control in medicine, and government is responding. The physician dislikes auditing his colleagues. HELP and its counterparts provide a means for providing quality review while corrective measures are still possible for the patient. A system of prompters, probably with a human intermediary such as a nurse-clinician, will prompt the physician when the situation calls for it.

Experience already has shown that such prompting is acceptable only if the evidence for suggesting a particular course of action is convincing. Because much of what we do is based on anecdotes and personal opinion, honest differences exist. Where variations in management plans are not based on scientific evidence, consideration of cost alone may be the appropriate deciding factor.

The ability of HELP to generate data for analysis of medical practice may prove to be its most valuable feature. The accuracy of such data will be enhanced as the decisions made from these data become an integral part of the care of the patients involved. Thus a positive feedback situation is created in which dependence on and utilization of the system by the responsible decision-maker leads to insistence on improved accuracy of data, which in turn facilitates improvement in the analyses done to derive an improved logical criteria for future decisions—and this improvement and verification of decision criteria will influence the physician to place even more confidence in the system.

Indeed, electrocardiographers set a powerful new force in motion when they first used the computer to make interpretations. They should, therefore, assume some of the responsibility for directing the use of this tool into productive channels that will work for the long-range benefit of all patients.

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