2

Computer-Assisted Clinical Decision Making

G. Anthony Gorry

In the early 1970s, a small number of medical computing research groups simultaneously realized that the field of artificial intelligence offered potential solutions to problems that had previously constrained the effectiveness and acceptance of medical decision-making programs. At Rutgers University, this arose when Kulikowski, a computer scientist who had previously worked with statistical pattern-recognition systems (Nordyke et al., 1971), noted that a consultation system for the diagnosis management of glaucoma would significantly benefit from enhanced knowledge of physiology and causality. At Stanford University, the new approaches arose from earlier work applying AI to chemistry in the DENDRAL program (Lindsay et al., 1980) and from Shortliffe's and Buchanan's disenchantment with the interactive features of traditional diagnostic programs that were based on statistical techniques (Shortliffe and Buchanan, 1975). At the University of Pittsburgh, Pople's previous work with computer models of neuroanatomy and abductive logic (Pople and Werner, 1972; Pople, 1973) led to the symbolic models used in INTERNIST. Meanwhile, at the Massachusetts Institute of Technology and Tufts–New England Medical Center, Gorry, Schwartz, and others had undertaken notable work applying formal decision theory to medical problems. A pair of landmark papers appeared in the American Journal of Medicine *in 1973 (Gorry et al., 1973; Schwartz et al., 1973). Those researchers were not totally satisfied with the decision-theory approach, however, and Gorry in particular was impressed by simultaneous work that was underway at M.I.T.'s Project MAC (now the Laboratory for Computer Science and the Artificial Intelligence Laboratory).*

From *Methods of Information in Medicine*, 12: 45–51 (1973). Used with permission.

We present here Gorry's insightful paper, which resulted from those dissatisfactions and from his observations about the potential utility of AI techniques. The paper discusses his group's experience with formal decision-theory models and their limitations. Gorry outlines briefly the motivation for the group's new work based on AI techniques, summarizes their early results, and outlines their plans for pursuing the research in the future. The Present Illness Program (Chapter 6) was the first result of this early work. Although the plan for future research was not completely clear at the time the article appeared in 1973, the issues outlined and the recognition that artificial intelligence techniques offered some potential solutions to the problems of representation and the human interface make this article an important early "bridge piece" between work using the traditional normative models and the newer approaches that are the subject of the rest of this book.

2.1 Motivation for the Research

In the past few years, there have appeared in the literature many discussions of the use of computers in the health care system and of the way in which they might improve the efficiency of that system. Such improvements are seen as arising from a wide variety of computer-based activities, such as scheduling of hospital admissions, control of laboratories, and maintenance of medical records. Although these activities (and others as well) can undoubtedly benefit from the introduction of well-designed computer systems, more fundamental problems remain. There is an increasing shortage of medical personnel and a geographical maldistribution because new doctors are reluctant to practice in rural or depressed urban communities. Also these discussions fail to indicate how a high level of physician competence can be maintained in the face of a continued expansion of medical knowledge. The gap between what a doctor should know and what can be retained and utilized is continually widening.

As Schwartz (1970) has noted, "The computer thus remains (in the light of conventional projections) as an adjunct to the present [health care] system, serving a palliative function, but not really solving the major problems of that system."

There is, in fact, little reason to believe that any of the current proposals for solving these problems, technological or other, will do more than mitigate their severity. Despite plans to reorganize patterns of medical care and efforts to enlarge medical school capacity and create new classes of "doctors' assistants," the physician shortage promises to be with us for decades and to pose a serious obstacle to health planning. The problem of maintaining and improving quality appears equally knotty since there is little indication that current programs in postgraduate education will be adequate to the challenge.

If conventional remedies will not meet the demands imposed by society's broad commitment to extensions of health care, it is clear that new, even heretical strategies must be devised. One intriguing possibility is to use the computer as an "intellectual" or "deductive" instrument—a consultant that is built into the very structure of the health care system and augments or replaces many of the traditional activities of the physician. One can envision an ongoing dialogue between the physician and the computer with the latter continuously taking note of history, physical findings, laboratory data, and the like, alerting the physician to probable diagnoses, and suggesting possible courses of action. One may hope that the computer, well-equipped to store a large volume of information and ingeniously programmed to assist in decision making, will help free the physician to concentrate on the application of bedside skills, the management of the emotional aspects of disease, and the exercise of good judgment in the nonquantifiable aspects of clinical care.

The computer, used in this manner, might also open the way to quite different means of employing nonphysician personnel. Use of the computer as an intellectual resource in diagnosis and treatment might well be coupled to the development of new types of highly specialized allied health personnel who could perform functions of a scope well beyond that currently considered feasible for doctors' assistants. Computer-supported "health care specialists," aided by a variety of automated devices for history taking, blood analysis, and other procedures, and trained to perform a careful physical examination, might take over a large segment of the responsibility for the delivery of primary medical care. Guided by the computer, constrained from exceeding their capacities by instructions built into the computer programs, and linked to regional consulting centers by appropriate display devices, the new breed of "health care specialists" could make a major contribution to the resolution of the seemingly insoluble problem of maldistribution and shortage of physicians.

While such visions of the future are heady stuff, a serious consideration of the problems to be solved is immediately sobering. Clearly, considerable intellectual and technological resources must be marshaled and a long-term research commitment must be made if such a scenario is to become a reality.

The work discussed in the next section constitutes a very modest investigation of one aspect of this problem. The focus of this work is on the decision-making aspects of clinical medicine. The original hope was to embody in a computer program a normative procedure for diagnostic and therapeutic decision making that could be applied to a variety of clinical problems (Gorry, 1968). Although this work was only a partial success, it proved a very valuable exercise from which a number of new ideas were gained. A discussion of these ideas will be postponed until the discussion of the new research plan. The discussion in the next section has not been "edited" to reflect the new (and hopefully better) view of the problem.

2.2 Review of Past Research

2.2.1 Introduction

The purpose of this section is to review our own research on the use of a computer to solve diagnostic and treatment problems in medicine. A major result of this research has been the development of a computer program that is intended to serve as a consultant in a number of medical problem areas. Here the considerations that underlie the program are discussed. The basic functions of the program are outlined in a nontechnical way, and an example of the use of the program is given. Then the results of the use of the program for several different medical problems are reviewed. Finally, an attempt is made to ascertain the potential of programs such as this in the delivery of appropriate medical care. Detailed reports on various aspects of this research are available in the literature (Gorry, 1967; 1968; Gorry and Barnett, 1968a; 1968b), and so the emphasis here will be on providing a general overview of the work and results obtained to date.

2.2.2 Modeling the Diagnostic and Treatment Problem

The use of digital computers in the selection of good diagnostic and treatment strategies has received increased attention in recent years. One reason for this interest is the general desire to improve the ability of the clinician to deal with the difficult problems that can arise in the management of a patient. A significant portion of the difficulty stems from the fact that the physician must sort out numerous possibilities and develop hypotheses about the state of health of the patient. The ability of the computer to store extremely large amounts of data, to enumerate many possibilities, and to perform complex logical operations suggests its potential value in this problem-solving process. Before a computer can be used to significant advantage in analyzing diagnostic and treatment strategies, however, precise procedures must be formulated for the means of inference required to deduce the clinical state of the patient from observed signs and symptoms, and a formalized capability must be developed for the prediction and assessment of possible therapeutic measures. In other words, the problem of performing diagnostic inference and weighing therapeutic strategies must be reduced to a problem of computation.

In order to better understand the requirements, a model of the diagnostic-treatment problem was formulated. The model is a mathematical one, but its principal characteristics can be discussed in terms of the way a physician deals with this problem, although it should be noted that the model was not developed as a description of the way in which physicians operate. The purpose of the model is to permit the exploitation of the particular capabilities of a computer. Hence, in the next several paragraphs, when I am discussing the way in which a physician or doctor deals with the problem, I am using *physician* or *doctor* instead of *model* for convenience, and I am not presenting a theory of human problem solving in the medical area. [The relationship of the model to the actual problem-solving behavior of the physicians is discussed in Gorry (1970).]

In general, a physician confronted with a potentially ill patient initially does not have sufficient information about the patient to decide on a diagnosis or on a therapeutic policy. The information the physician does have, however, in addition to his or her general medical knowledge and experience, enables formulation of some tentative hypotheses about the state of health of the patient. This opinion will exert a considerable effect on the strategy the physician will employ in dealing with the patient. For convenience, let us say that the options available to the physician are tests and treatments. By *test* we mean any means for obtaining additional information about the patient ranging from simple questions to laboratory procedures or certain surgical procedures. The physician employs those tests that are expected to provide results of significant value in improving the current view of the patient's problem. The term *treatment* will be used to refer to any means at the doctor's disposal to correct the health state of any patient. Treatments range from drugs to a variety of surgical procedures. The selection of an appropriate treatment for a given problem is strongly dependent on the correctness of the doctor's opinion about the patient's problem. The selection of the wrong treatment, for whatever reason, can have very serious consequences for the patient.

The value of the information obtained from a test is determined by the contribution this information makes to improving the doctor's current view of the patient's problem and hence to reducing the risk of misdiagnosis with its associated cost. Hence the doctor is inclined to perform many tests. On the other hand, the tests available generally are not without some cost in terms of patient discomfort, time of skilled persons, money, etc. Thus there is a conflicting tendency to hold the number of diagnostic tests to a minimum.

As is discussed in Gorry and Barnett (1968b), the doctor resolves these conflicting tendencies by performing sequential diagnosis. At a particular point in time, given the current view of the patient's problem, the physician can evaluate the choices available. The basic choice is to employ a test to obtain more information or to select a treatment in the hopes of curing the patient.

If the physician elects to cease testing and to make a diagnosis, the choice of a treatment implies a certain risk of mistreatment through a misdiagnosis. On the other hand, the doctor can perform some test in the hopes of gaining additional information on which to base a diagnosis and the resulting choice of treatment. In this case, the doctor incurs the cost (in some terms) of the test selected. When the results of the test are known, and when they have been incorporated into the current view of the problem, the physician is faced with a decision problem of exactly the same form as the one just solved. Thus a doctor can be thought of as solving a sequence of similar decision problems. At each stage of the process, the cost of further testing is balanced against the expected reduction in the cost of treatment due to the test results. When, in the opinion of the physician, no test possesses the property that is expected to reduce the risk of treatment by an amount that exceeds its cost, the physician will cease testing, make a diagnosis, and treat the patient. If the physician repeatedly updates the current view of the problem in keeping with the latest information available, and if the physician has sufficient knowledge, effective diagnostic and therapeutic strategies may be developed.

Although this description of the manner in which a physician deals with diagnosis-treatment problems is simplified and somewhat artificial, it does emphasize the fundamental role that sequential decision making plays in the process. It seemed clear that it was necessary for a computer program to exploit an analogous capability (framed in terms suitable for a machine) in solving more general problems of the type.

2.2.3 The Development of the Computer Program

In this section, the basic components of a computer program to assess diagnostic and therapeutic strategies are discussed. These components directly reflect the view of the required problem-solving process outlined in the preceding section. The discussion of the program is nontechnical. Readers interested in the technical details are referred to Gorry (1967; 1968).

The program has three basic components. The first is called the *information structure,* and it constitutes the medical experience of the program. By changing the information structure, one can convert the program for use in a new problem area. This is the only part of the program that changes from one application to the next.

In addition to the diseases, signs, symptoms, tests, and treatments, the information structure contains two types of information: probabilities and utilities. The probabilities relate signs and symptoms to diseases. For example, one probability might be the conditional probability of red blood cell casts in the urine given that the patient has acute tubular necrosis. The program's understanding of various diseases is entirely in terms of the conditional probabilities that relate to the variety of signs and symptoms and treatment consequences to those diseases.

The utilities of the tests, treatments, and treatment consequences are thought of as the subjective preferences of an expert. The utility of a test reflects the pain associated with the test, the cost of the test, the time of a skilled person required for the test, the risk of the test to the patient, etc. Similar factors are reflected in the utilities of the treatments and the treatment consequences. Utility can be thought of as the common denominator in terms of which all these diverse factors are measured. Utility assessment will be considered in more detail later. Here we simply note that if the program is to make comparisons of factors such as risk and cost, a common scale must be established for seemingly diverse outcomes.

The second major segment of the program is called the *inference function.* Basically the task of the inference function is to establish the diagnostic significance of a particular test result. In a typical situation, a doctor confronted with a particular diagnostic problem must interpret the available evidence (observed signs and symptoms, etc.) in terms of past personal medical experience. In other words, the doctor employs a method of deduction that can accommodate both a general understanding of diseases and the individual instance represented by the current patient. The inference function of the program is the analogue of this capability in the physician. It uses probabilistic inference based on Bayes' Rule (Gorry, 1967; Gorry and Barnett, 1968a) to obtain a probability distribution for the likelihood of each disease given the evidence to date and general medical experience. The latter is incorporated in the information structure of the program. It is this probability distribution, then, that constitutes the current view taken by the program of the given problem. This view is updated whenever any new evidence is made available to the program. The updated probability distribution is one of the major factors that influence the strategy chosen by the program for dealing with a given patient.

The third component of the program is called the *test/treatment selection function.* Its purpose is to select at each stage in the problem-solving process an appropriate test or treatment for use on the patient. By considering the probability distribution associated with the current view of the problem and the utilities of the various treatment consequences, this function can determine the best treatment to perform, assuming that no further tests are to be used. The treatment chosen is the one that minimizes the expected risk, and it provides the standard used in evaluating the potential value of further testing.

In evaluating the potential usefulness of a particular test, the program considers the current view, the utilities of the various tests, and the likelihood of the possible test results. For each possible result of a test, the program can simulate the change in the current distribution that would occur if this result were obtained. The expected risk of treatment can be estimated for this new distribution. For each result of a test, the expected

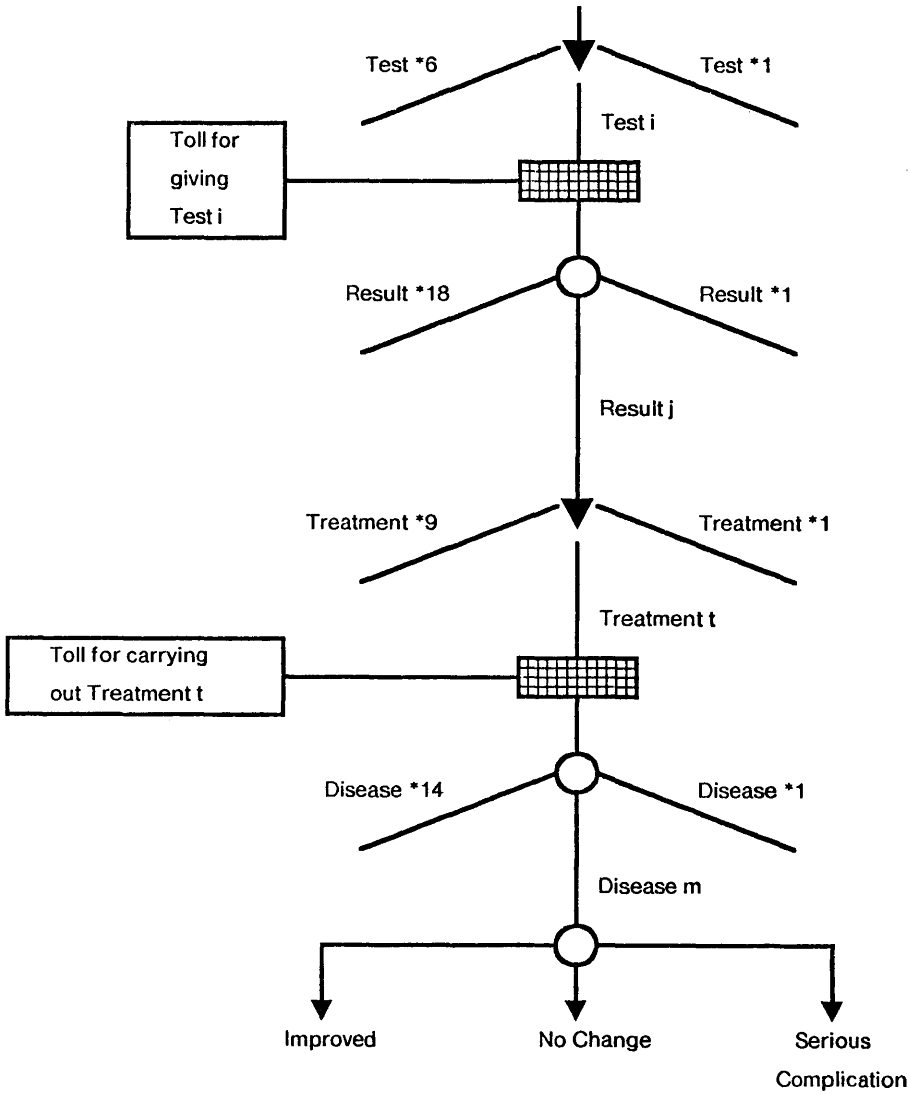

FIGURE 2-1 Example of a decision tree.

risk of treatment given the result is weighted by the likelihood of obtaining that result, and the sum of these products is added to the utility of the test to obtain the overall measure. A schematic representation of the factors considered in evaluating a test is presented in Figure 2-1. By analyzing decision trees such as the one shown, the program attempts to select the best test or treatment at each stage of the analysis.

In Figure 2-2, an actual dialogue between a user and the program is presented.[1] The problem being considered is the diagnosis of a case of congenital heart disease. At the outset of the discussion, the program is essentially passive, simply accumulating whatever evidence the user offers and using the inference function to update its current view of the problem. When the user has completed the initial description of the patient, the test/treatment function is invoked to determine the best diagnosis-treatment policy. In this case, no treatments were considered, and the problem was merely one of diagnosis. The example, however, does give a basic impression of the use of the program.

2.2.4 Experience with the Program

The program has performed extremely well in the medical problems to which it has been applied. It was used as a diagnostic program (no treatments were considered) in two areas: primary bone tumors and congenital heart disease. The bone tumor problem involved the classification of patients into one of nine disease groups based on radiographic evidence and other physical findings. Studies made with the program indicated that it performed at the level of an experienced radiologist given the same evidence (Gorry, 1967). The second medical problem considered was the diagnosis of congenital heart disease. Here there are 35 diseases in question. Again the results showed that the program performed at the level of an expert (Gorry, 1967; 1968). Both the bone tumor problem and the congenital heart disease problem had certain characteristics that made them unsatisfactory tests of the program's capability, however. First, in neither area were the costs of the tests sufficiently high to make the sequential aspect of the program particularly important. Because tests were so cheap, it mattered little how many were performed or in what order. Second, the treatment problem was not considered because the doctors needed to help define these treatments and their consequences were not available.

Because of these difficulties, a third medical area was considered, the diagnosis and treatment of acute renal failure. The management of the acute renal failure syndrome is an important medical problem. Although the incidence of the problem is relatively small in the context of all disease treatment problems, the potential risk to the patient's life is sufficiently great to give the problem special significance. In dealing with this problem, the physician must account for this risk factor as well as the possibility that the tests that could be employed to gain further information about the patient can contribute to the medical problem if improperly used.

The definition of the acute renal failure problem used in this study included 15 diseases. As in the previous problems of bone tumors and

[1]The ELIZA program, developed by Professor Joseph Weizenbaum of M.I.T., was used to facilitate user input.

PLEASE TELL ME ABOUT THE PATIENT.
Well he is about 65 years old.
PLEASE CONTINUE.
No cyanosis.
O.K. PLEASE GO ON.
What is your opinion of the 3 most probable diseases now.
  2 WITH PROBABILITY .68
  18 WITH PROBABILITY .10
  24 WITH PROBABILITY .04
ALL RIGHT. GO ON PLEASE.
Name four diseases for me.
ATRIAL SEPTAL DEFECT WITH PULMONARY HYPERTENSION.
PLEASE CONTINUE.
I meant the name of disease 24.
VENTRICULAR SEPTAL DEFECT WITH PULMONARY FLOW LE. 1.4 SYSTEMIC FLOW.
O.K. PLEASE GO ON.
What more do you need to know.
CHECK THE HILAR VESSELS. ARE THEY INCREASED OR DECREASED.
That information is not available.
LOOK FOR A LEFT SECOND SYSTOLIC MURMUR.
What is your current view.
MY CURRENT VIEW IS

DISEASE	PROB	DISEASE	PROB
2	.68	34	.03
18	.10	5	.03
24	.04	12	.02
25	.04		

NOW LET'S GO ON.
LOOK FOR A LEFT SECOND SYSTOLIC MURMUR.
Say there is a left second systolic murmur.
I SEE.
IS THE AXIS IN THE ECG RIGHT, LEFT, OR NORMAL.
What is the probability of atrial septal defect now.
IT IS 85.
ALL RIGHT. GO ON PLEASE.
IS THE AXIS IN THE ECG RIGHT, LEFT, OR NORMAL.
Left.
ALL RIGHT.
CHECK FOR A LEFT FOURTH SYSTOLIC MURMUR.
What are the 3 most probable diseases now.
  5 WITH PROBABILITY .43
  2 WITH PROBABILITY .39
  18 WITH PROBABILITY .05
PLEASE CONTINUE.
CHECK FOR A LEFT FOURTH SYSTOLIC MURMUR.
What is the medical name of disease 5.
ATRIO-VENTRICULAR COMMUNIS.
O.K. PLEASE GO ON.
CHECK FOR A LEFT FOURTH SYSTOLIC MURMUR.
Say there is one.
O.K.
IS THERE AN ACCENTUATED OR DIMINISHED P2.
What is the probability of disease 5 now.
IT IS 71.
ALL RIGHT. GO ON PLEASE.

FIGURE 2-2 Example of a session with the program. (Program's responses and questions are in capital letters.)

```
IS THERE AN ACCENTUATED OR DIMINISHED P2.
Not available.
I RECOMMEND A DIAGNOSIS OF DISEASE 5.
What are the 3 most probable diseases.
        5 WITH PROBABILITY .71
        2 WITH PROBABILITY .23
       24 WITH PROBABILITY .01
I'm finished. Thanks for your help.
I HOPE THAT I HAVE BEEN OF SERVICE. GOODBYE.
```

FIGURE 2-2 continued

congenital heart disease, the information structure for the program included the relevant probabilities. In this case, however, no attempt was made to obtain these probabilities from an analysis of historical data. Rather, the opinion of an expert was used in establishing each probability. In addition, special attention was paid to the assessment of the required utilities. Again, the opinion of an expert renal specialist served as the basis for these numbers.

The precise manner in which these judgments were obtained from the expert and the way in which they were converted to utilities are discussed in Betaque and Gorry (1971). Here I want to outline the procedure briefly. The renal expert was given a series of hypothetical decision problems. Each problem required that a choice be made between a particular event for certain (such as curing the patient by performing a certain operation) and accepting a chance in a *lottery*. If the expert chose the lottery, a given event would be chosen for him with probability P, and some other event would be chosen with probability $1 - P$. Before making a choice, the expert is told exactly what the two events in the lottery are and what the value of P is. With the theory discussed in Betaque and Gorry (1971), a series of these decision problems can be used to establish the utilities of tests, treatments, and consequences required by the program.

With the information structure for the renal failure problem developed in this way, the program duplicated the diagnostic-treatment decisions of expert renal specialists in over 90% of the cases tested. Furthermore, when the information structures from two experts were used, the program agreed more closely with the expert whose judgments it was using than did the other expert.

2.3 Plan for Further Research

To provide a context for a discussion of our plan for further research in this area, I want to offer a criticism of the work to date. Without going into detail, let me say that the evaluations of the program were strongly biased in favor of the program. The number of diseases, their rigid definitions, and the types of tests and treatments used all combined to make simple, exhaustive search an effective strategy. Thus the program did quite well compared to the experts, but the method it employed differed from the ones they used. Although we cannot characterize precisely the methods used by the experts, it is clear that these methods can accommodate the greater complexity of real clinical situations. The potential usefulness of exhaustive search as the primary decision procedure for the program, however, is open to question. In this regard, it is instructive to consider some of the failures of the program in the experiments described above.

One such case was a patient with acute glomerulonephritis (AGN), a common cause of acute renal failure. Patients with AGN seldom have severe hypertension, but the patient presented to the physicians and the program did. The program obtained the correct diagnosis, but the treatment it recommended differed from that proposed by the doctors. Although both the physicians and the program chose the same treatment for AGN, the physicians recognized the need to deal with the patient's hypertension and hence recommended a second treatment as well.

Clearly, the program could be modified to check for this problem and to make the appropriate decisions. The same could be done for several other problems of this type that were identified. Similar modifications would be required to obtain the appropriate interpretation of certain signs and symptoms. For example, hematuria (red blood cells in the urine) is an important diagnostic finding in acute renal failure. On the other hand, a patient with an indwelling catheter will generally have hematuria regardless of his or her intrinsic disease. Hence the interpretation of this finding should reflect this fact. Again, either the program or the data it uses must be changed. Although these particular problems could easily be solved within the context of the existing problem, they raise an important question. How many such "minor" modifications will be required for the program to have practical use in the clinical management of acute renal failure?

For a period of several months, we have investigated the amount and type of knowledge possessed by two acknowledged renal experts. Although much more work needs to be done, I can offer certain tentative conclusions. These conclusions provide motivation for a change of direction in this research.

1. Although detailed knowledge of physiology and pathophysiology is sometimes useful in clinical decision making, gross knowledge of this kind coupled with a large number of experiential facts and mini–decision procedures forms the primary basis of clinical judgment in renal disease.
2. The knowledge used by the experts is both factual and procedural. Their experience has provided them with a rich repertoire of ideas of the form "if x is present and y is absent, then a good trial hypothesis is

D." Such rules allow them to focus their attention on relatively few diagnoses or treatments. Of course, these rules are heuristics, but many of them are of considerable value in dealing with experts' decision-making problems. By remembering large numbers of such patterns or rules, they avoid search to a large extent.
3. This experiential knowledge is not framed in deterministic terms, but is associated with various degrees of certainty.
4. The renal experts can specify only part of this knowledge *a priori*. A large part of this knowledge can be elicited only in response to apparent misconceptions on my part (or as embodied in the program).
5. Although there are very many "pieces" of knowledge involved, these experts seem able to state them clearly when the occasion arises.

The physicians with whom I have been working are acknowledged experts in renal disease, and their performance in this field far surpasses that of a very large fraction of the doctors who treat patients with this problem.[2] It is important, then, to get as much of their knowledge as possible in distributable form (i.e., a program).

The original program was based on a particular normative view of clinical decision making. The judgments of experts could be added only to the extent that these judgments could be expressed as simple probabilistic relationships or as utilities. Procedural knowledge was added through reprogramming. Thus the addition of knowledge was either implicit (setting probabilities or utilities to cause the program to arrive at a conclusion that a physician could obtain more directly) or laborious (reprogramming). Unfortunately, I am convinced that, for the foreseeable future, the desire to add knowledge will be great, and an attempt to maintain the program (perhaps for its simple, aesthetic appeal) will prove frustrating at best.

Although this discussion has been brief, it indicates the general tenor of the problems I foresee with the approach we had been using. Decision analysis is a useful tool when the problem has been reduced to a small, well-defined one of action selection. It cannot be the sole basis of a program to assist clinicians generally in an area such as renal disease.

2.3.1 A New Program for Renal Disease

Several months ago, we began the development of a prototype program for use in the problem of acute renal disease. This program is currently in a most rudimentary form. Therefore I will be discussing here not so much an existing program as some goals toward which we are working. Our short-term goal is to produce a version of this prototype that can be

[2]This is not a condemnation of the latter group. It is a simply a reflection of the fact that most people with kidney disease do not have access to the experts and resources of a major teaching hospital.

used by renal specialists in an informal way as a means to assess the potential of the ideas on which it is based.

Recent developments by people in the Artificial Intelligence Laboratory at M.I.T. have opened the way for the exploration of new approaches to computer assimilation of knowledge. The developments comprise both a way of looking at the problem of machine knowledge and some very high-level programming systems (Sussman et al., 1971; Winograd, 1971). The prototype system incorporates some of these new ideas and as a result is better able to accept experiential knowledge directly from the user. The details of the new program are beyond the scope of this paper (and may change significantly over time). Here, I will restrict myself to the conceptual framework within which this program is being built.

A simple language has been implemented to permit renal experts to give advice to the program regarding facts or ways to proceed in a particular circumstance. Examples of such statements are the following:

a. In acute glomerulonephritis, if hematuria is gross then red blood cell casts are very likely;

b. If proteinuria is heavy and hematuria is gross and red blood cell casts are present and diagnosis is acute renal failure, then diagnosis of glomerulonephritis is very likely.

The basic functions of the program are (1) to accept such statements, (2) to note appropriate associations among various statements, and (3) to use the statements deductively when appropriate to draw conclusions about diagnosis or management.

It must be emphasized that the new program is very primitive as yet. The new technology mentioned above has greatly facilitated its development, however, and it seems likely that a much improved program can be implemented. The real question is whether sufficient improvement can be realized to make the program useful. At present, we cannot answer this question, but I can indicate the chief problem areas to be explored.

2.3.2 Problems for Investigation

Concept Identification

We intend to continue to try to identify the important concepts in renal disease. By this, I mean the identification of the central, problem-specific ideas in terms of which the experts organize their knowledge. One example is the concept of renal function. There are several approaches to inferring renal function and assessing whether it is stable or changing. This determination is very important in diagnosis and in choosing management strategies. It is possible to obtain from the experts the procedure by which they infer a value for renal function. Further, many statements about the interpretation of changes in renal function can be made. To capture the knowledge embodied in these statements, some computer realization of the concept of renal function must be developed.

Already it is clear that there are many such concepts. We will be trying to identify the most important ones and to develop reasonable ways to represent them in the program. Needless to say, a major question will be how many such concepts are required in the program and the complexity of their realization. One possibility is that the number is so large as to be impossible to deal with at present. Another is that the individual concepts are based on an implicit assumption of enormous knowledge about the world. We believe that the number of important concepts is indeed large, but not beyond our capabilities. For example, a very large portion of the basic knowledge about kidney disease is contained in one book (admittedly a large one). Further, the expert clinicians believe that big chunks of that book are unnecessary for the support of *clinical* activities.

The issue of how much common sense is assumed in these concepts is also important. On the one hand, it could be argued that to understand these concepts a program must understand a tremendous amount about the world. On the other hand, the relatively precise language of medicine may be the key here. The program may know many facts about streptococcal infection and its role in acute renal failure without understanding the concept of germs. The physician using the program may have little need to ask the program for the latter. More generally, the user will have considerable knowledge organized in terms of fairly well-defined words and phrases. The knowledge of the program can be expressed in these terms to assist the physician. More detailed knowledge on the part of the program may be unnecessary.

Already it is clear that there are many concepts, but that not all are of great importance. We will be trying to identify the most important ones and to develop reasonable ways to represent them in a program.

Language Development

Because we believe that the continual addition of knowledge is critical, we will be working on the development of a language within which experts can express this knowledge to the program. An understanding of the important concepts in renal disease, of course, is a prerequisite for the design of such a language. In general terms, what we are seeking is an automatic programming capability so experts can *program* the machine directly. At present, we can envision three languages involved in this process.

First, at the lowest level there will be the computer language in which the concepts are realized. At a higher level will be a language in which statements concerning these concepts are made without explicit recognition of the details of the lower-level realization. Such a language may well be an extension of the simple IF/THEN-type language already implemented. Maintaining this separation may lessen the problems arising from changes in the particular realization of the concepts in the machine. The third-level language will be English. We are hoping to use Winograd's program (Winograd, 1971) to translate statements made by the experts (in a subset of English) into the intermediate language mentioned. The second-level language can be viewed as a canonical representation of the subset of English that can be accepted. Such a translation will require an interaction with both of the lower-level languages, but we can say little in detail about this process. We do believe, however, that, whatever the realization, language will be critical if the knowledge of experts is to be captured. Also, we believe that they must be given some form of English for input and inquiry. Hence the tasks of concept identification and language development will have highest priority.

One question is worth raising here, although at present we do not know the answer. This question concerns the necessity for English. With experts dedicated to the project being the sole source of knowledge input, there might be little need for English; they could be taught to use the second-level language. On the other hand, if interaction with other clinicians proves to be important (and we believe it will) then English may be very important. The question of how much is to be gained from English is one that will be considered carefully.

Explanation

The other side of the coin is explanation. If experts are to use and improve the program directly, then it must be able to explain the reasons for its actions. Furthermore, this explanation must be in terms the physicians can understand. The steps in a deduction and the facts employed must be identified for the expert so that he or she can correct one or more of them if necessary. As a corollary, the user must be able to easily find out what the program knows about a particular subject.

2.3.3 A Comment on Goals

The original aim of this research was to produce a decision-making program. Although this is still the long-term goal, we believe the time required to achieve this goal is sufficiently long to necessitate the establishment of some short-term goals. Presently, we consider a reasonable (but somewhat vague) goal to be the construction of a program that can accept knowledge and answer simple requests for parts of that knowledge. Because there will be many cases where the program will lack knowledge relevant to a particular clinical situation, it should make not pronouncements but rather suggestions of things to consider and the assumptions on which its suggestions are based.

ACKNOWLEDGMENTS

My colleagues, Dr. William B. Schwartz and Dr. Jerome P. Kassirer of the Tufts–New England Medical Center have made major contributions to the work discussed. Any inadequacies in the discussion, however, are my responsibility alone.