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EVALUATING THE PERFORMANCE OF A COMPUTER-BASED CONSULTANT

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ABSTRACT

The performance of a computer-based clinical consultation system is evaluated. The program, called MYCIN, is designed to function as an aid for infectious disease diagnosis and therapy selection, with an initial emphasis on bacteremias. The evaluation methodology is discussed, as well as the difficulties encountered in attempting to evaluate clinical judgments. Specialists in infectious diseases judged MYCIN's final therapy recommendation, and intermediate conclusions about the significance of the infection and identity of infecting organisms. The evaluation techniques described may be useful in assessing the performance of other clinical decision aids. Results of the evaluation show that the program's therapy recommendations meet Stanford experts' standards of acceptable practice 90.9% of the time (Table II), with some variation noted both among individual experts and between Stanford experts and others (Tables I and II).

INDEXING INFORMATION

Antimicrobial Selection, Artificial Intelligence, Clinical Decision Making, Computer-Aided Diagnosis, Evaluation, Infectious Disease.

1 INTRODUCTION

Studies documenting the problem of antibiotic misuse by physicians have periodically appeared in the medical literature since the 1950's [1]-[15]. The problem has been magnified as the number of new antibiotics introduced each year continues to increase; 12 new antimicrobials were approved for clinical use in the U.S. in 1974-1976. There have been a number of responses to this problem including medical education for physicians [16], pharmacist-physician interactions [17],[18], surveillance systems [8],[19], and restriction of drug use [20],[21]. In this report we briefly describe another approach -- a computer-based consultation system, named MYCIN, that will help physicians select antimicrobials for patients with infections.

The material in this paper is focused on two central issues. First, it describes one of the earliest medical applications of techniques from the subfield of computer science known as "artificial intelligence".[2] The MYCIN program is designed to be a high performance aid for clinical decision making. Although the description of MYCIN here is brief, references are cited to provide more detailed information about the system and its emphasis upon acceptability to physician-users.

In addition, the methods and results of a study to evaluate MYCIN's current level of performance as an infectious diseases consultant are presented. The evaluation methods are themselves of interest because they were developed in an attempt to analyze clinical decisions in which there

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[2]See [22] for a discussion of another clinical application using related techniques.

is not clearly a "right" or "wrong" answer. Since some areas of medicine are characterized by variety of approach, even among experts, the techniques described may be generally useful in assessing the quality of decision making by other computer programs.

It is important to evaluate the adequacy of the knowledge base in a complex reasoning program in order to assure correct decisions. The study described here measures the adequacy of MYCIN's 200 bacteremia rules without asking experts to judge each rule out of context. The broader question of overall acceptability of the program is not addressed by this study, but will require assessment before MYCIN becomes a working tool for physicians.

2 MATERIALS AND METHODS

2.1 The Program

The MYCIN system[3] is a computer-based consultation and explanation program which provides antimicrobial recommendations for patients with infectious diseases. Its design and capabilities have been documented in detail elsewhere [23]-[26].

After MYCIN asks for clinical and laboratory data concerning the patient (Fig. 1), it attempts to determine whether an infection is present that requires treatment, the significance of isolated organisms, and their likely identities (Fig. 2). On the basis of these findings, the system recommends an antimicrobial regimen for the patient. (Fig.3).

[Take in Figures 1,2, and 3 about here]

The physician can also request alternate therapy recommendations, explanations of MYCIN's reasoning processes, and justifications of its recommendations. A simplified, schematic representation of the MYCIN algorithm is shown in Fig. 4. MYCIN's therapeutic decisions are based on three types of information: dynamic data, static factual information, and judgmental knowledge. Dynamic data about the particular patient (e.g.,

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[3] MYCIN is written in Interlisp and runs on a Digital Equipment Corporation KI-10 at the SUMEX Computer Facility at Stanford University.

** CASE 9 - AN 80 YEAR OLD DIABETIC WHITE MALE, S/P IRRADIATION FOR LARYNGEAL CARCINOMA ONE YEAR AGO, ADMITTED WITH FEVER AND LETHARGY. HAS DEVELOPED LEFT LOWER LOBE INFILTRATE AND PRODUCTIVE COUGH WITH KLEBSIELLA GROWING ON SPUTUM CULTURE. NOW 4 OF 4 BLOOD CULTURES ARE POSITIVE FOR GRAM NEGATIVE RODS.

.
.
.

9) Enter the identity of ORGANISM-1 from the sputum culture (CULTURE-1):
** KLEBSIELLA-PNEUMONIAE

.
.
.

13) Enter the identity of ORGANISM-2 from the blood culture (CULTURE-2):
** UNKNOWN

.
.
.

26) Has Case 9 had any gu surgery or manipulation of the urinary tract (e.g.,. indwelling catheter, cystoscopy, etc.)?
** NO

.
.
.

30) During the present illness, has Case 9 been treated with an antimicrobial agent which is no longer being administered?
** YES
31) What agent?
** AMPICILLIN

.
.
.

Figure 1

My therapy recommendation will be based on the following probable infection(s) and potential causative organism(s):

INFECTION-1 is PNEUMONIA with BACTEREMIA

<Item 1> KLEBSIELLA-PNEUMONIAE [ORGANISM-1, ORGANISM-2]
<Item 2> PSEUDOMONAS-AERUGINOSA [ORGANISM-2]
<Item 3> E.COLI [ORGANISM-2]
<Item 4> PROTEUS-NON MIRABILIS [ORGANISM-2]

Figure 2

[Rec 1] My preferred therapy recommendation is as follows:

In order to cover for Items <1 2 3 4>:
Give the following in combination:
1) GENTAMICIN
Dose: 90 mg (1.7 mg/kg) q8h IV (or IM) for 10 days
2) CARBENICILLIN
Dose: 4.51 g (85 mg/kg) q4h IV for 10 days

Figure 3

symptoms, signs, and laboratory data) are entered by the physician and can vary with each clinical situation. Static factual knowledge (e.g., normal and pathogenic flora of nonsterile body sites) are the lists or tables which change little over time and are static within any single consultation. Judgmental knowledge used for making decisions from existing data is contained in 200 rules (Fig. 5).

[Take in Figures 4 and 5 about here]

One working assumption is that the accuracy of the program depends on the factual information and judgmental rules. To test the program's accuracy prior to introduction of MYCIN in a clinical setting, a formal evaluation protocol was developed. This is described below.

2.2 The Evaluation

Fifteen patients at Stanford University Medical Center or the Palo Alto Veterans Administration Hospital were selected for the evaluation. Each had a positive blood culture.[4] For each patient, an abstract was

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[4]Consecutive patients with positive blood cultures were selected unless 1) they were outpatients when the blood culture was reported positive (we wanted easy access to the inpatient chart and hence adequate documentation of clinical details of all patients in the study); 2) they had a previous positive blood culture within seven days (we did not want to give the evaluators an excessive amount of patient information); or 3) they had a clinical diagnosis of meningitis or endocarditis (the system had not yet been given the rules to deal with the complexities of those disorders).

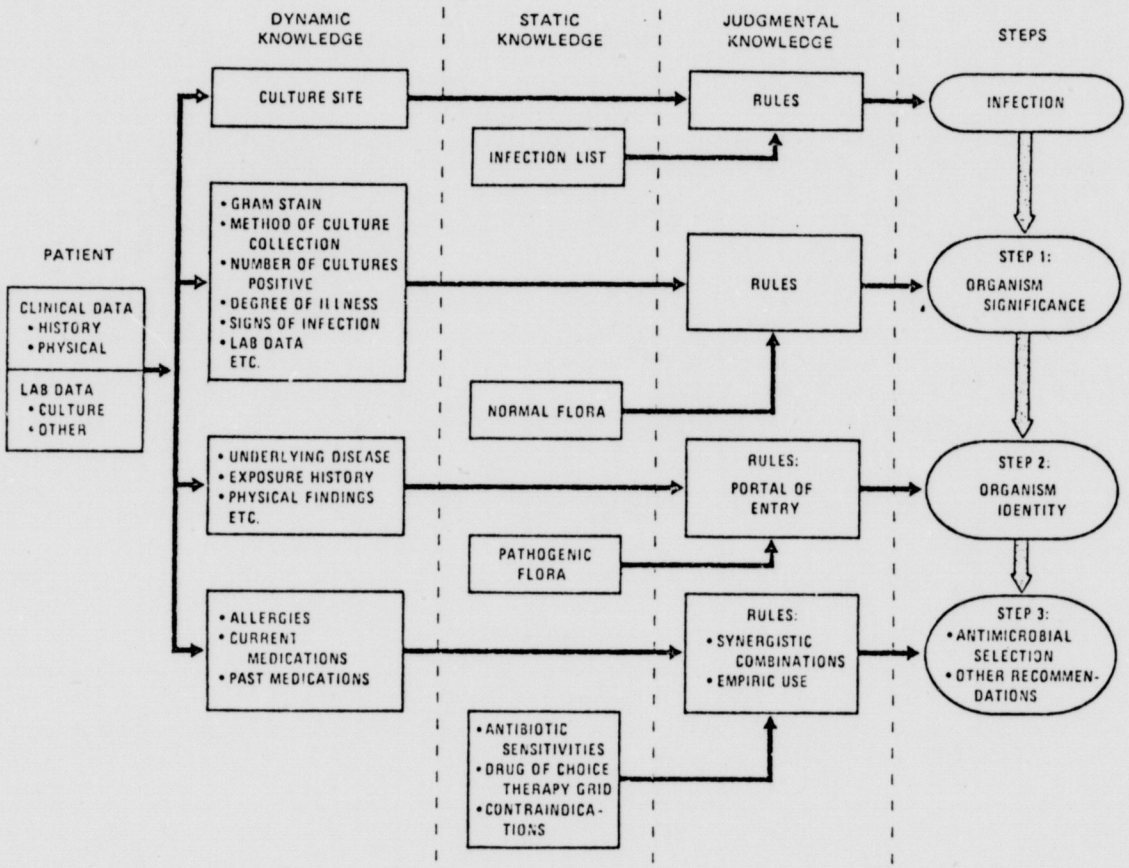
DYNAMIC KNOWLEDGE
STATIC KNOWLEDGE
JUDGMENTAL KNOWLEDGE
STEPS
PATIENT
CLINICAL DATA
• HISTORY
• PHYSICAL
LAB DATA
• CULTURE
• OTHER
CULTURE SITE
• GRAM STAIN
• METHOD OF CULTURE COLLECTION
• NUMBER OF CULTURES POSITIVE
• DEGREE OF ILLNESS
• SIGNS OF INFECTION
• LAB DATA
ETC.
• UNDERLYING DISEASE
• EXPOSURE HISTORY
• PHYSICAL FINDINGS
ETC.
• ALLERGIES
• CURRENT MEDICATIONS
• PAST MEDICATIONS
INFECTION LIST
NORMAL FLORA
PATHOGENIC FLORA
• ANTIBIOTIC SENSITIVITIES
• DRUG OF CHOICE THERAPY GRID
• CONTRAINDICATIONS
RULES
RULES
RULES: PORTAL OF ENTRY
RULES:
• SYNERGISTIC COMBINATIONS
• EMPIRIC USE
INFECTION
STEP 1: ORGANISM SIGNIFICANCE
STEP 2: ORGANISM IDENTITY
STEP 3:
• ANTIMICROBIAL SELECTION
• OTHER RECOMMENDATIONS

Figure 4

Rule 417

If: 1) The stain of the organism is grampos, and
2) The morphology of the organism is coccus, and
3) the growth conformation of the organism is pairs, and
4) The site of the culture is one of: sputum lung-tissue
Then: There is suggestive evidence (0.7) that the identity of the organism is streptococcus-pneumoniae

Figure 5

prepared that included a summary of the patient's medical history, physical examination, and hospital course up to the time of the positive blood culture report. Also included were the vital signs graph, medication sheet, and laboratory data. In case evaluators required further information, all physician progress notes were available for perusal. The evaluation form consisted of a questionnaire interwoven into the transcript of the computer consultation. The expert recorded his own conclusions at various stages of the consultation before he saw MYCIN's decisions.

This evaluation form was submitted to five physicians subspecializing in infectious diseases at Stanford who had no prior involvement with MYCIN. To test for possible biases or differences in approach unique to Stanford, five infectious disease specialists from other academic institutions also participated in the evaluation.

The decision-making process of the MYCIN program can be divided into three major steps: determination of (1) organism significance, (2) organism identity, and (3) appropriate therapy selection (Fig. 4). The evaluation form was structured similarly, enabling separate evaluation of performance at each step. This is important because a complex reasoning program must be judged by the accuracy of its intermediate conclusions as well as its final decisions.

Because of the complexity of the task, there is often no single "correct" conclusion to be made about a patient. Experts may disagree among themselves in two important respects. First, experts may select a slightly different approach to diagnosis or therapy from among a group of

generally acceptable alternatives. Thus we allowed them to indicate that an alternative decision is acceptable, even if not identical with their own. Second, experts sometimes disagree over conclusions that, for them, have no acceptable alternatives, for example, whether an infected patient requires coverage for an E. coli, even if none has actually been isolated from any cultures. Thus we present the opinions of a majority of experts (Table II) as well as opinions of individual experts (Table I). In Table I, the percentage of instances in which the program's conclusions were either identical to an expert's or were acceptable alternatives is represented. Table II summarizes the percentage of cases in which a majority of experts judged MYCIN's conclusions identical or acceptable alternatives to their own. Data for the Stanford and non-Stanford groups are kept separate to allow assessment of the extent to which the program reflects a bias toward local practices.

[Place Tables I and II about here]

3 RESULTS

Step 1: Organism Significance

MYCIN concluded that 4 of the 15 patients had organisms in their blood cultures which were not likely to be pathogens and therefore recommended no therapy. As shown in Table I, the individual experts agreed with MYCIN's determination of organism significance in 97.3% of the instances. As shown in Table II, a majority of the experts also concluded that no therapy was indicated for these four patients.

An important initial decision for an infectious disease consultant is whether the isolated organisms require treatment at all. Many culture sites are nonsterile with bacterial flora normally present. Also, contaminant organisms are occasionally introduced into the culture during collection or during laboratory processing. Thus, often the risks of giving a potentially toxic drug must be balanced against the possibility that the organism isolated is not a true pathogen. In this series of cases, MYCIN's ability to determine the significance of a particular organism in causing infection was virtually identical to that of participating infectious disease specialists.

Step 2: Organism Identity

The second row in Tables I and II summarizes the data on MYCIN's ability to infer the correct identities of the pathogenic organisms. In the eleven treated cases, MYCIN identified a total of 45 organisms that required therapy. With ten experts rating each of these choices, the total number of expert/organism judgments (N) was 450. In 76.7% of the instances the system's choices were identical to the experts' or were acceptable

alternatives (Table I). In 90.9% of the cases, its results were acceptable to the majority of the experts (Table II). Although additional organisms were suggested by some experts for some of the patients, in no case did a majority of experts suggest the same additional organism.

Appropriate selection of antimicrobial agents requires determining the likely identities of the pathogenic organisms, using the patient's history and physical exam plus the physician's clinical experience. Selection is more difficult when therapy must be initiated in the absence of definitive identification of the organisms, as is often true in bacteremic infections. For over 90% of the cases in this series, a majority of the experts identified the same potential pathogenic organisms as did MYCIN.

Step 3: Therapy Selection

In 8 of the 11 cases requiring treatment, the majority of the experts were willing to accept MYCIN's recommendation as an acceptable alternative. In 2 of the 11 cases, a majority of the experts rated MYCIN's therapy as unsatisfactory.[5] In one case, the experts were equally divided as to whether MYCIN's therapy selection was satisfactory or unsatisfactory.[6]

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[5]One "unsatisfactory" case involved a situation in which MYCIN overlooked the fact that aerobic organisms can occasionally grow in "anaerobic" culture media such as supplemented peptone broth and not grow in standard culture media such as brain-heart-infusion broth. MYCIN did not have the appropriate rules for dealing with this situation and therefore failed to cover for all of the possible organisms causing the infection. This was subsequently easily corrected by the addition of such rules. The other patient had a penicillin allergy and MYCIN elected not to give the combination of carbenicillin (a penicillin) with gentamicin. Four experts did give carbenicillin and three of them rated MYCIN's therapy as unsatisfactory.

[6]MYCIN concluded that it was appropriate to cover for Enterococcus in a patient with gram-positive cocci in the blood and a coagulase positive staphylococcal abscess. Some of the experts did not believe this was necessary.

There existed significant differences in ratings given by Stanford experts versus non-Stanford experts in this case. Four of five Stanford experts rated MYCIN's therapy selection as satisfactory, while four of five non-Stanford experts rated MYCIN's therapy as unsatisfactory. This "geographic" bias may have occurred because MYCIN's rules reflect the prescribing habits prevalent among, or unique to, Stanford infectious disease specialists.

The number of drugs prescribed for each patient by MYCIN and by the experts was also compared, since a common prescribing error is to use more antibiotics than necessary. In those patients judged to require antimicrobial therapy, MYCIN selected an average of 1.5 drugs per patient (range one-two) while the experts selected an average of 1.6 drugs per patient (range one-three).

In addition to the quantitative data presented in Tables I and II, we gathered qualitative answers to questions about overall impressions. There were no cases in which a majority of the experts suggested a particular clinical question that MYCIN had failed to ask and which would be important in determining therapy selection. Although the ten experts suggested an average of seven additional questions per patient, there was no consensus among them on the content of the missing questions. Likewise, although a few experts indicated that MYCIN asked some extraneous questions, there was no consensus among experts about which questions were irrelevant.

MYCIN's overall performance was considered acceptable in 93% (14/15) of the cases. The one "overall unacceptable" case is one of the two for which therapy selection was judged unacceptable. It involved a facultative

organism that grew only in the anaerobic bottle, as discussed in Footnote 5. In addition, most of the experts indicated their belief that MYCIN, in its current status, provides "some" or "considerable" utility as both a clinical and educational tool.

4 DISCUSSION

Computers have lived up to early expectations in only a small number of medical areas, including hospital administration, biomedical engineering, and clinical laboratory management. However, observers had predicted that computers would be a major technological advance that would help in the solution of many other medical problems[27]. For some of these problems, particularly those in the clinical domain and those requiring direct physician interaction, computer technology has not yet been as helpful as was once anticipated. Such programs have suffered from a number of recurring problems[28]:

1) The accuracy physicians demand of a clinical program has seldom been attained or documented;

2) The problem domain has been so narrow and constrained that the program has had only limited application;

3) The decision strategies used by computer programs are often not easily understood by physicians; and

4) The interaction with the computer has often been tedious and time-consuming.

The evaluation study described here addresses the first problem of

accuracy. As shown in the previous section, MYCIN's accuracy approaches that of infectious disease experts at Stanford and, by implication, may surpass that of practicing physicians who are not experts. The remaining problems have substantially affected the design of MYCIN but the acceptability and usefulness of MYCIN in the clinical setting have not yet been demonstrated.[7]

As was mentioned, the problem of antibiotic misuse has received extensive publicity. Bacteremia is an important part of this larger problem area. However, evaluation of a program whose knowledge is limited to bacteremia is complicated by the fact that it often occurs in conjunction with other infections such as endocarditis. It should therefore be noted that the program we have discussed is only the first step in building a system that is knowledgeable about infectious diseases.

A desire to make MYCIN's reasoning steps explicit has been a major factor in the design of the program. MYCIN can explain the basis for its clinical decisions when asked to do so. The physician can thus accept or reject the program's recommendations after reviewing the reasoning steps[24].

Human engineering features which facilitate the human-computer interaction have also been designed into the system from the start. All of MYCIN's questions are phrased in standard English and require only a brief response. If a question is not clear, it can be rephrased and a list of expected responses can be printed on request. Minor typographical or

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[7]For an extensive discussion of design considerations for MYCIN, see [23].

spelling errors are corrected automatically[23]. Although the program now requires about 30 minutes to run, we are working to reduce this time to make it more acceptable for physicians, or for ancillary personnel running the program at a physician's request.

Further limitations to the present MYCIN approach include the requirement that the physician take the initiative in asking for advice, as well as the need for a large computer of a type not currently found in most hospital computing environments (see [23], Chapter 7).

The evaluation technique described here was designed to assess the current level of MYCIN's performance. It also taught us some design considerations for any similar studies undertaken in the future. Foremost among these is the need to make the study "blind" in the sense that the experts do not know whether they are evaluating human or computer decisions. The benefits of this would be twofold. First, it would permit a parallel comparison of experts' decisions and the computer's decisions as seen by other experts. Second, there are some inherent biases introduced when an evaluator knows he is assessing a computer's performance, and the present study did not control for this variable. We are currently embarking on the evaluation of MYCIN's recent additions regarding therapy for meningitis; this new study design will reflect the lessons learned in the evaluation discussed above.

FIGURE CAPTIONS

Figure 1. A case summary and selected questions from the consultation session. The physician's responses are in upper-case letters and follow a double asterisk (**); all other text is generated by the computer. The case summary typed by the physician is not understood by the program; it is merely stored for future reference.

Figure 2. After MYCIN decides that the infection is significant, it displays its conclusions regarding likely causative organisms. ORGANISM-1 is the KLEBSIELLA isolated from the sputum and ORGANISM-2 is the UNKNOWN organism from the blood, as shown in Fig. 1. For a variety of clinical reasons, MYCIN decides it is unsafe to assume the organism in the blood is the same as the KLEBSIELLA from the patient's pneumonia.

Figure 3. MYCIN recommends a therapy regimen for the patient. During the process of therapy selection, the site of infection, the susceptibility of the organism to antibiotics and the patient's clinical status (e.g., renal function, age) and drug history are considered.

Figure 4. A simplified, schematic representation of how MYCIN selects an antimicrobial.

Figure 5. A MYCIN rule. Each rule consists of a premise and a conclusion. The conclusion will be drawn only if the conditions in the premise are satisfied. For example, in rule 417, MYCIN will conclude that the identity of an organism might be Streptococcus pneumoniae if conditions 1 to 4 in the premise are all fulfilled. Other rules will also be tried in order to conclude the identity of the organism. The strength of a conclusion of a rule is indicated by a number between 0 and 1 (see [23], Chapter 4). The larger the number, the greater the belief in the conclusion. In this rule the evidence is suggestive (.7), but not absolutely certain, that the identity is Streptococcus pneumoniae.

TABLE I. COMPARISON WITH INDIVIDUAL EXPERTS

% of Instances in Which MYCIN's Selection Was Identical to, Or an Acceptable Alternative to, an Expert's First Choice

	5 Stanford Experts	5 National Experts	All 10 Experts
Organism Significance (1)	96.0% N = 75	98.7% N = 75	97.3% N = 150
Organism Identity	80.9% N = 225	72.4% N = 225	76.7% N = 450
Therapy Selection	76.4% N = 55	69.1% N = 55	72.7% N = 110

(1) For organism significance, the experts were asked only if the patient should be treated or not. "Acceptable alternative" was not thought to be meaningful here.

TABLE II. COMPARISON WITH A MAJORITY OF EXPERTS

% of Cases in Which MYCIN's Selection Was Identical to, or an Acceptable Alternative to, the First Choice of a Majority of Experts

	At least 3 out of 5 Stanford Experts	At least 3 out of 5 National Experts	At least 6 out of All 10 Experts
Organism Significance	100% N = 15	100% N = 15	100% N = 15
Organism Identity(*)	100% N = 11	90.9% N = 11	90.9% N = 11
Therapy Selection (*)	90.9% N = 11	72.7% N = 11	72.7% N = 11

(*) Eleven patients had significant infections, for which MYCIN attempted to determine organism identity and appropriate therapy.

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