Clinical Application of Decision Analysis: A Detailed Illustration

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The clinician must always optimize the patient's chance for the best possible outcome, but the complex task of deciding which diagnostic study to perform and which therapeutic agent to administer is usually carried out using imperfect information. These critical decisions are usually made in a covert fashion without explicit consideration of the multiple factors that impact on the outcome. Decision analysis is a quantitative method for making such diagnostic and therapeutic judgments, incorporating both probabilistic data and value judgments in the analysis of clinical problems. This article presents a brief overview of decision analysis and a detailed illustration of its use in an actual complex clinical situation. The clinical problem described consists of the management of suspected pulmonary embolism in a patient with a high risk of complications from both pulmonary arteriography and long-term anticoagulation. The example chosen also points up the virtue of decision analysis in considering prospectively both the information content and the attendant risks of contemplated diagnostic procedures.

THE PHYSICIAN, required to make complex medical decisions in the face of incomplete information, often opts to gather more data from a variety of laboratory tests or specialized examinations. Unfortunately, the additional data obtained are imperfect (i.e., both false positives (FP) and false negatives (FN) occur), and the testing procedure itself may lead to untoward complications. Thus, the values and risks of any contemplated study must be weighed carefully. The physician is further confronted by a large number of possible therapeutic choices, each with its own potential value and its own attendant risks.

In recent years, decision analysis has been introduced to amplify the physician's decision-making capabilities.[1–5] This discipline provides a mechanism for describing complex clinical problems in an explicit fashion, identifying the available courses of action (both tests and treatments), assessing the probability and value of all possible outcomes, and making a simple calculation to select the optimal choice.

We will first present a general overview of the method and then illustrate it with an actual clinical example of suspected pulmonary emboli in an elderly woman who is unusually prone to develop complications from both pulmonary arteriography and long-term anticoagulation. After demonstrating in this clinical example how to apply decision analysis to make a choice among several diagnostic and therapeutic approaches, we will analyze in detail the factors utilized in making the decision.

DESCRIPTION OF THE TECHNIQUE

The first step in decision analysis is to structure the decision-making process using a decision tree. An example of a decision tree that might be used to decide whether or not to perform a pulmonary arteriogram in a patient with suspected pulmonary embolism is shown in Fig. 1. Consideration has been limited to a small set of important choices and possible outcomes. The tree shown in Fig. 1 contains two kinds of nodes or branch points—decision nodes and chance nodes. Decision nodes are denoted as squares and represent a point at which the clinician must make a choice. For example, node D-1 denotes the choice of whether or not to carry out a pulmonary arteriogram. Chance nodes are denoted by circles and represent possible outcomes that are not under the control of the clinician. For example, node C-1 denotes the chance that the patient may die as a result of the arteriogram.

Having developed a structure for the problem, the clinician next must consider the data required to make these choices. The chance occurrences referred to above can be assessed as probabilities, on a scale from zero to one. Such probabilities can be obtained by summarizing the outcomes experienced by similar patients in the past; they can be derived from case material in the medical literature or, if such data are not available, from the estimates of an expert. Probabilities derived from expert opinion can

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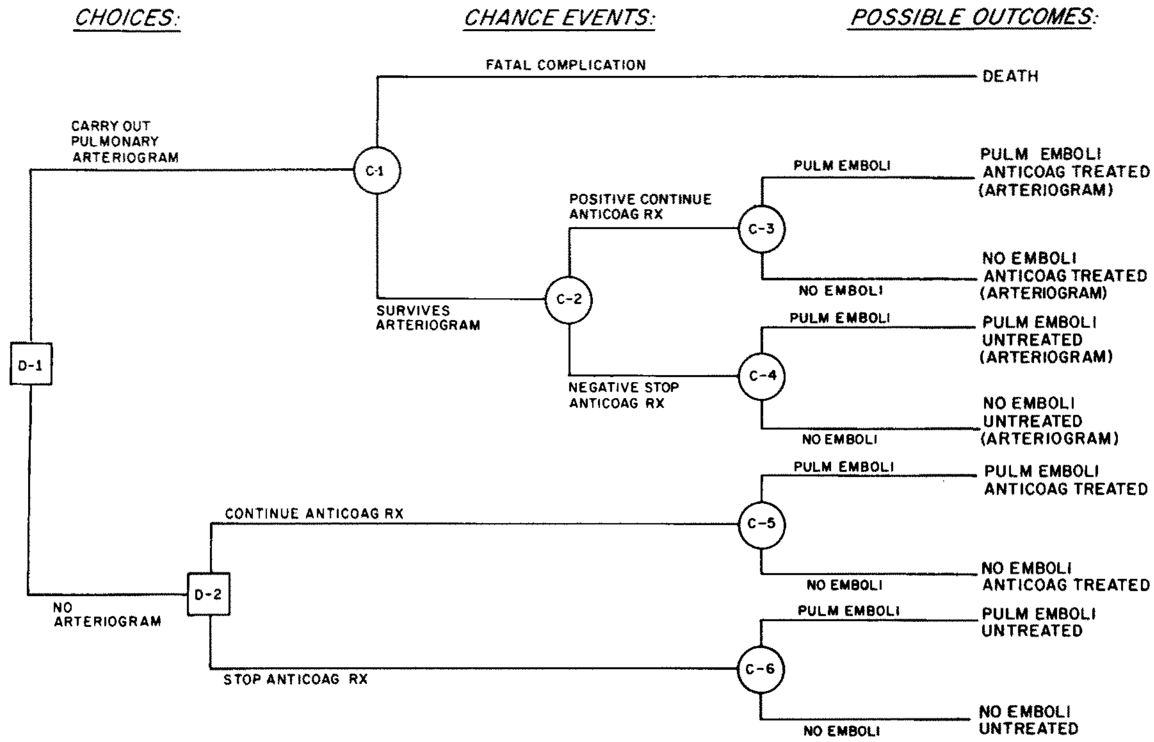

Fig. 1. The decision tree. This figure describes the problem of whether or not to anticoagulate a woman with suspected pulmonary emboli. The square nodes describe the decisions facing the physician. The circular nodes describe chance events. The labels on the right describe the possible outcomes under consideration.

also be viewed as predictive, that is, as an index of the clinician's expectation of the likelihood of any given outcome. Certainly the descriptive data in the literature must form the predominant basis for probability assessments, but the patient under consideration is often not a typical case—possibly because another disease is present or because of differences in the clinical or laboratory findings. If the probabilities are viewed as predictive statements, the "fine-tuning" adjustments of probabilities required to fit the clinical picture of an individual patient are readily justified.

Next we must consider the utilities (worth or value) of each of the potential outcomes shown on the tree. To maximize the chance of a good outcome and minimize the chance of a poor outcome, it is necessary to specify which outcomes are best and which are worst. If some outcomes are neither best nor worst but fall into some intermediate class, then we must be able to place them on a scale showing the relative worth of each.

The first step in determining the utility of each of the potential outcomes is to decide what the source of these value assessments should be. In various circumstances, the answer might be the physician, the patient, or society. For most circumstances involving individual patients, the physician attempts to optimize the outcome for the patient and tends to disregard the consequences to society. Assuming this construct, the physician must decide how to specify the utility of each outcome. Single measures, such as 5-yr survival, life expectancy, or even quality-adjusted life expectancy, can be used; but every effort must be made to incorporate the values of the patient. Although it might seem impossible to obtain such an assessment from lay individuals unfamiliar with medical terminology, survival curves, and mortality and morbidity statistics, several studies have indicated that it is possible to approach patients directly with a series of questions designed to help them assess the utility of each potential outcome.[6,7] If circumstances preclude such a direct approach, the physician must make these assessments.

The next step in the analysis is to combine the probability of each outcome with the utility of that outcome and thereby calculate an expected utility for each node in the tree. The expected utility is an index of the average outcome of a given situation if it were to occur many times. It is a basic concept of decision analysis that the option selected should be the one with the highest expected utility because this choice should, on the average, produce an optimal outcome. This process emphasizes the important concept that in order to optimize the chance for a good outcome, it is necessary to consider the probabilities and utilities of all "downstream" consequences at the time when the original choice is made.

Finally, it is important to examine the impact of possible errors in the data on the decision. A technique called sensitivity analysis aids in this process. It is a tool used to determine which parameters (e.g., a given probability or utility) can be reasonably expected to affect a decision. If a reasonable putative error in a parameter (i.e., an error in a given probability or a utility) alters the optimum choice, the decision is considered sensitive to changes in that parameter. If the substituted values do not affect the optimal decision, the decision is considered insensitive to that parameter. Decisions that are insensitive can be approached with considerably greater confidence than can sensitive ones. Indeed, when the decision is sensitive to changes in one or more probabilities or utilities, additional data gathering may be required—either from additional consultation, additional testing, or more detailed discussion of the views of the patient. The identification of "soft" data to which the decision is sensitive can also be a stimulus for detailed studies of a given problem in a large group of similar patients.

CASE REPORT

M. M., a 70-yr-old woman with "borderline" schizophrenia and chronic heart block controlled with a pacemaker was admitted to the New England Medical Center Hospital with severe biventricular cardiac failure that had developed over the previous month. On the day of admission she developed hemoptysis, and on examination she had bilateral pleural friction rubs and premature ventricular beats. Treatment with lidocaine controlled the rhythm disturbance, but the patient developed hypotension and pulsus paradoxus. Echocardiogram gave no evidence of pericardial effusion. A vigorous diuresis was induced with furosemide, and digitalis therapy was begun. Bedside catheterization of the pulmonary artery showed the pulmonary artery pressure to be 60/30 and the pulmonary capillary wedge pressure to be 25 mm Hg.

The diagnosis of pulmonary embolism was considered, and heparin was administered. One week later the patient's condition was less unstable and consideration was given to substantiating this diagnosis. Lung scan was carried out; however, for didactic purposes, the results of this study will be described later. The possibility of carrying out pulmonary arteriography was also considered but the risk of this procedure was thought to be increased. Review of previous records disclosed that the compliance of both the patient and her husband with the advice of physicians was uneven, and for this reason the risk of bleeding from long-term anticoagulation was thought to be substantially increased.

REPRESENTATION OF THE CLINICAL PROBLEM: THE DECISION TREE

Ordinarily, the risk of pulmonary arteriography is very small, and this procedure can be carried out with impunity. Similarly, the risk of long-term anticoagulation is quite low, and this treatment can usually be given without detailed consideration. In this patient, both the risk of the test (arteriography) and the risk of treatment (continued anticoagulant therapy) were thought to be substantially increased, and thus the impact of these risks on the decision either to carry out the test or to continue treatment without the test could not be readily ascertained without a structured approach.

This complex problem can be considered by the use of the decision tree shown in Fig. 1. The first decision facing the physician (node D-1) is whether or not to perform a pulmonary arteriogram, with the implication that if the study is positive, long-term anticoagulation would be an appropriate choice; whereas if negative, anticoagulation would be discontinued. As shown by the uppermost node (C-1), if arteriography is done, the patient might suffer a fatal complication of the arteriogram (upper branch) or might survive. If the patient survives (lower branch), the arteriogram might be interpreted as positive or negative (node C-2). If it is positive, the patient may actually have had pulmonary emboli and will be treated (node C-3, upper branch). Alternatively, the patient may not have had emboli (i.e., the result is a FP) but nevertheless she will be treated (node C-3, lower branch). If the arteriogram is negative and anticoagulants are discontinued, the patient may still have had emboli (the study was FN) and she will go untreated (node C-4, upper branch); similarly, if the test is a true negative (TN), no treatment will be given (node C-4, lower branch). Finally, if arteriography is not performed, another decision must be faced, that is, whether or not anticoagulation should be continued (node D-2). In this case, the patient may be anticoagulated when emboli are present or absent (node C-5), or may not be anticoagulated when emboli are present or absent (node C-6).

The reader should appreciate that neither the decision to carry out a lung scan nor the possible results of the scan are included in this tree. Although these elements could have been included, we omitted them because the scan is virtually risk free, and thus this test does not contribute to the outcome in terms of morbidity or mortality. In fact, the results of the scan impact only on the likelihood of pulmonary emboli (see below). Omission of these items simplifies the structure of the tree without adversely affecting the representation of the clinical problem.

ANALYSIS OF THE DECISION TREE

Assignment of Numerical Values for Probabilities

Because data sufficiently specific to be relevant to the precise attributes of the patient were not available, in some instances the estimates of experienced radiologists and cardiologists responsible for the patient's care were used. Based on the clinical setting, it was estimated that the likelihood of recurrent pulmonary emboli was approximately 70%. This probability (0.7) is denoted as the "prior probability."

Selecting a value for the mortality rate of pulmonary arteriography in this patient was difficult. Ordinarily, the risk of death from this study is only approximately 0.4%.[8,9] However, because this elderly patient had marked ventricular ectopy, severe cardiac failure, a possible recent myocardial infarction, and persistent pulmonary hypertension, the mortality rate of pulmonary arteriography was taken to be approximately 5%. Furthermore, because 1 wk had elapsed since the last suspected embolus, some resolution of emboli might be expected. This factor, combined with observer error, was thought to contribute to some increase in the likelihood of a FN arteriogram. The FN rate was taken to be 20% (i.e., a sensitivity of 80%) and the false positive rate was taken to be 1% (a specificity of 99%).[9,10]

The next step in analysis is the determination of the probability of each potential outcome. The probabilities of each outcome are given for each branch in Fig. 2. Because the derivation of the probabilities differs somewhat from node to node, each node will be described separately.

Node C-1. The chance of a fatal complication is taken at 5%, thus the upper branch is assigned a probability of 0.05 and the lower branch 0.95.

Node C-2. To assess the likelihood of a positive arteriogram, the assumptions used are those described earlier concerning the likelihood of emboli and the error rates of arteriography in this patient. Of the 70% of patients who have emboli, 80% will have positive arteriograms, whereas of the 30% of the patients who do not have emboli, only 1% will have positive arteriograms. Thus, the probability of a positive arteriogram will be $(70\% \times 80\%) + (30\% \times 1\%)$ or 0.56 (top branch) and the probability of a negative arteriogram will be 0.44 (lower branch).

Nodes C-3 and C-4. The assignment of probabilities for nodes C-3 and C-4 is made by Bayes' rule. Only node C-4 will be considered in detail. The prior probability of emboli was 0.7, and the probabilities of a negative arteriogram given patients with and without emboli were assumed to be 0.2 and 0.99, respectively. Thus, the revised probability of emboli (upper branch) given the positive result is:

$$\frac{(0.7 \times 0.2)}{(0.7 \times 0.2) + (0.3 \times 0.99)} \text{ or } 0.32$$

Of course, the probability of no emboli (lower branch) is 0.68.

Nodes C-5 and C-6. The probabilities used in these nodes are the prior probabilities.

Assessment of Utilities

Because neither the patient nor her family were considered capable of comprehending the issues involved, the value judgements regarding both morbidity and mortality were made without their input. For each outcome, both life expectancy and the expected time free of morbidity were calculated. These calculations in-

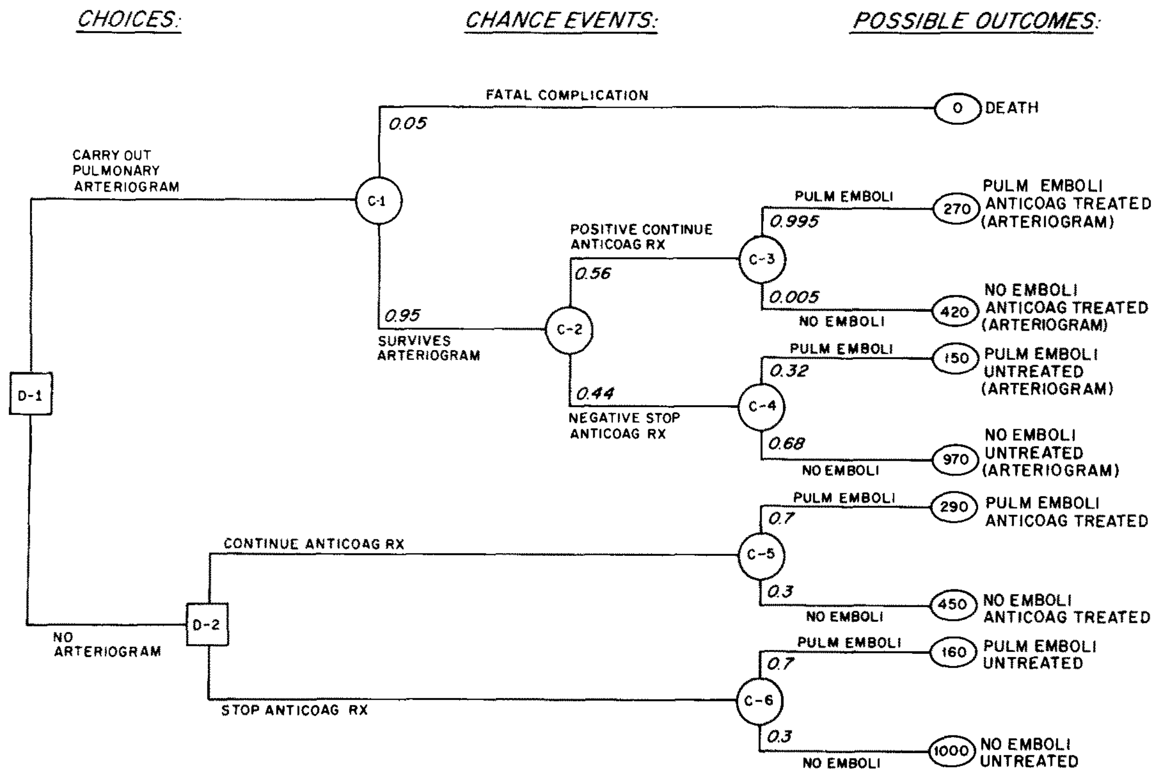

Fig. 2. Probabilities and utilities. Addition of probabilities and utilities to Fig. 1 is the next step in the analysis. The italicized numbers on each branch represent the probability that each event will occur. The values in the ovals denote the utility, or relative value, assigned to each potential outcome.

volved numerous assumptions, but the results were reasonable estimates of the overall situation. These morbidity- and mortality-related values were combined as a product, and the value obtained was adjusted on a scale from 0 to 1000 and used as a measure of utility.

Estimates of annual mortality and morbidity rates for the relevant circumstances are shown in Table 1. Annual rates were used because it is possible to combine the effect of several influences simply by adding the respective excess rates to the baseline rates.[11] Furthermore, expectations of survival and freedom from morbidity can be calculated by taking the reciprocal of the combined rates.

The baseline mortality rate shown in Table 1

Table 1. Mortality and Morbidity Rates*

Conditions:	Estimated Mortality Rate	Estimated Morbidity Rate
Baseline state of patient	100	400
Excess for pulmonary emboli, untreated	200	400
Excess for pulmonary emboli, treated	50	100
Excess for anticoagulation	50	200

Outcomes:	Mortality Total Rate	Expected Survival (yr)†	Morbidity Total Rate	Expected Time Free of Morbidity (yr)†
No emboli untreated	100	10.0	400	2.5
No emboli treated	100 + 50	6.7	400 + 200	1.67
Pulmonary emboli treated	100 + 50 + 50	5.0	400 + 100 + 200	1.43
Pulmonary emboli untreated	100 + 200	3.3	400 + 400	1.25

* Per 1000 patients per year.

† Calculated as the reciprocal of the total rate.

Table 2. Calculations of Utilities

Outcome	Life Expectancy (yr)	Expected Time Free of Morbidity (yr)*	Product	Utility Product × 40†
No emboli, untreated	10	2.5	25	1000
No emboli, untreated (arteriogram)	10	2.42	24.2	970
No emboli, anticoagulant treated	6.7	1.67	11.19	450
No emboli, anticoagulant treated (arteriogram)	6.7	1.58	10.59	420
Pulmonary emboli, anticoagulant treated	5	1.43	7.15	290
Pulmonary emboli, anticoagulant treated (arteriogram)	5	1.35	6.75	270
Pulmonary emboli, untreated	3.3	1.25	4.12	160
Pulmonary emboli, untreated (arteriogram)	3.3	1.17	3.86	150
Death after arteriogram	0	0	0	0

*The values for expected time free of morbidity shown in Table 1 have been decreased by 1 mo for the patients subjected to pulmonary arteriography to account for the nonfatal complications of this procedure.

† Utilities are normalized to maximum of 1000, utility of most favorable outcome.

was derived as follows:[11] (1) The annual mortality rate for 70-yr-old white females was taken to be 20/1000/yr. (2) The excess mortality rate for patients with an AV block treated with a pacemaker is approximately 15/1000/yr. (3) The excess mortality rate for congestive heart failure in such patients is approximately 65/1000/yr. Thus, the overall baseline mortality for this patient is calculated to be 20 + 15 + 65, or 100/1000/yr.

The long-term mortality for heparin-treated pulmonary emboli from 2 wk through 1 yr is approximately 50/1000/yr.[10] The assumption has also been made that the excess mortality and morbidity rates of untreated emboli are reduced to 25% of their original value if treatment is given. This assumption is consistent with the known efficacy of the anticoagulation in the treatment of pulmonary emboli.[12–17] The excess mortality rate for anticoagulation and the mortality rate for arteriography are clinical estimates based on the patient's clinical situation, and these data are examined subsequently. The morbidity data are also clinical estimates.

Table 2 summarizes the utility calculations for each potential outcome shown in Fig. 1. The nonfatal complications of pulmonary arteriography have been incorporated for this fragile patient by subtracting 1 mo from the calculated time free of morbidity. The right column in the table is the utility adjusted to a 0–1000 scale by multiplying each value by 40. These final utilities are shown in Fig. 2 within ovals on the right side of the figure.

Calculation of Expected Utility

The final step of the analysis is the calculation of expected utility for each node in the tree (Fig. 3).

For chance nodes, the expected utility of the node is calculated by summing the product of the probability and the utility of each of the branches emanating from that node. As an example, consider node C-3. The expected utility of the upper branch is (0.995 × 270) or 269 and of the lower branch is (0.005 × 420) or 2, and thus, the expected utility of the entire node is 269 + 2 = 271. The expected utility of the other chance nodes is calculated in the same fashion. Calculations proceed from right to left, and the result for each node is shown in Fig. 3; the expected utility for each node is shown in an oval pointing to that node.

For decision nodes, the physician should opt for the action with the higher expected utility, and for this reason the higher value of the two expected utilities is assigned to any decision node. Facing the decision at node D-2, for example, the physician should opt not to treat because the expected utility of C-6 (412) exceeds that of C-5 (338), and the value of 412 is assumed as the value of this decision node. The net result of all the calculations is that the expected value of node C-1 (440) exceeds that of node D-2 by a narrow margin, and thus it is apparent that the optimal decision (still ignoring the diagnostic value of lung scan) is to carry out the pulmonary arteriogram.

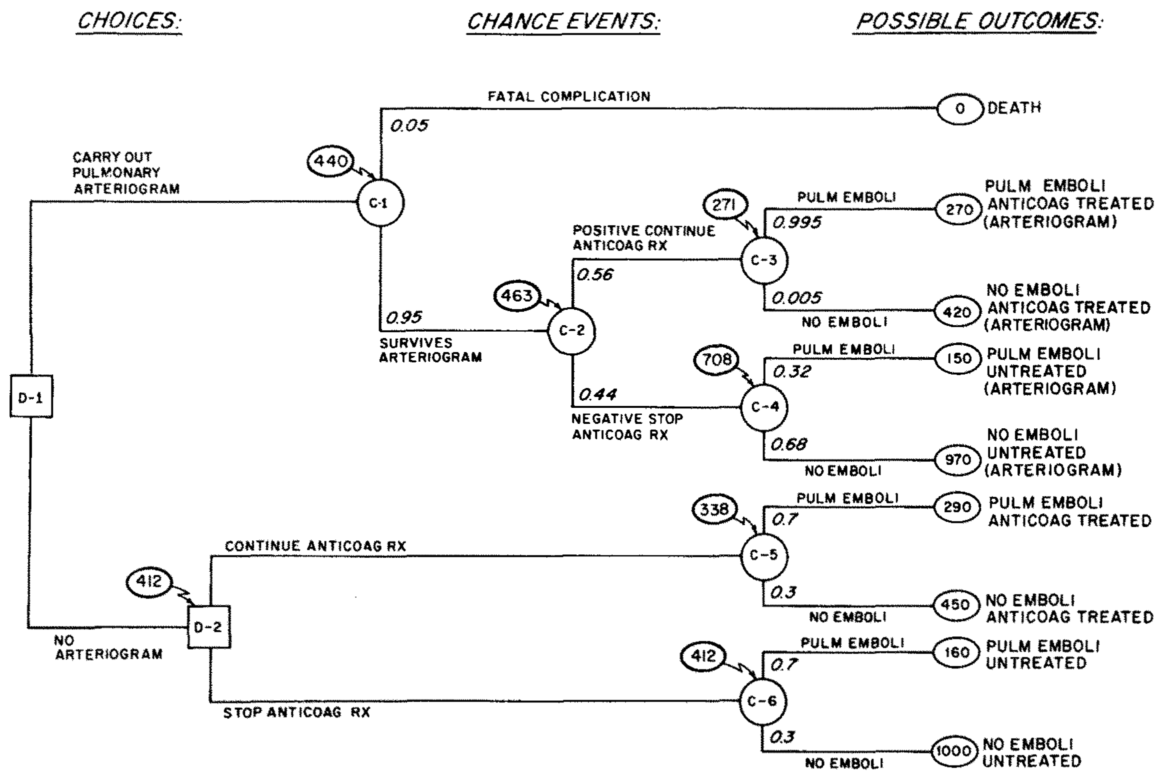

Fig. 3. Calculation of expected utility. Calculations are made from right to left. For each node, the calculated expected utility is shown within the oval pointing to the node. For chance nodes, the expected utility is the sum of the probability times the expected utility for each of the branches. For decision nodes, the expected utility is the largest of the expected utilities assigned to the two branches.

DETAILED ANALYSIS OF THE DECISION

In analyzing this actual clinical case, we were often forced to rely on the clinical judgment of the patient's physicians to tailor their knowledge of the medical literature to the specifics of this particular patient. We shall now examine the impact of some of these assumptions (i.e., the clinical likelihood of emboli, the potential impact of additional diagnostic information from the lung scan, and the complication rates for anticoagulant therapy and for pulmonary arteriography) on this decision.

Sensitivity Analysis of the Prior Probability and the Threshold Concept

The validity of the decision arrived at above can be assessed by the technique of sensitivity analysis. The prior probability is selected for examination first because, of all the probabilities used in the analysis, it is one of the softest numerical values, having been derived principally from subjective considerations. This first sensitivity analysis will be carried out in reference to Fig. 4; however before the analysis is done, both the principle of making a choice and the concept of thresholds will be illustrated.

In constructing Fig. 4, the expected utility of each choice (carrying out pulmonary arteriography, continuing anticoagulation, and discontinuing anticoagulation) was calculated using all possible estimates of the prior probability of pulmonary emboli; all other probabilities and utilities were kept constant. These calculations produce three straight lines, each representing the expected utility of one of the three choices available as a function of the prior probability of emboli. The optimal choice at any prior probability of pulmonary emboli is the one with the highest utility and is thus denoted by the diagnostic or therapeutic approach defined by the uppermost line in the figure. For the reader unfamiliar with this type of presentation, an illustration of these concepts may be helpful. If, for example, the prior probability of pulmonary embolism is 0.0 (i.e., if it is certain that the patient does not have emboli), then the optimal

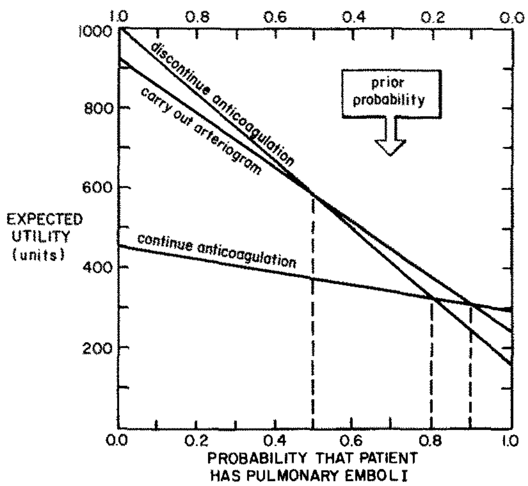

Fig. 4. Sensitivity analysis. The effect of the prior probability of pulmonary emboli on the optimal decision is summarized in this figure. The horizontal axis denotes the prior probability of pulmonary emboli, and the vertical axis denotes the value of each therapeutic or diagnostic option. Each option (discontinuing anticoagulant therapy, carrying out the arteriogram, or continuing anticoagulation) is summarized by a straight line. For any given probability of emboli, the optimal choice is described by the line with the highest value. The arrow denotes the prior probability (0.7) in the patient decribed here. The dotted lines denote the three thresholds: for prior probabilities below 0.5, anticoagulants should be stopped; for prior probabilities above 0.9, anticoagulants should be continued; for prior probabilities between 0.5 and 0.9, pulmonary arteriography should be carried out.

choice, with an expected utility of 1000, is to discontinue anticoagulant therapy. On the other hand, if the prior probability is 1.0 (i.e., if it is certain that pulmonary emboli are present) the optimal choice, with an expected utility of 290, is to continue anticoagulant therapy. In our clinical example, the prior probability of pulmonary emboli was 0.7 (denoted by the arrow), and the optimal choice is thus to carry out a pulmonary arteriogram. At this intermediate prior probability, the choice of arteriography has a utility of 440 units, a value higher than the utility of either discontinuing antigoagulant therapy (412 units) or continuing anticoagulant therapy (338 units).

It is apparent from inspection of Fig. 4 that there are three intersections between the lines denoting the original choices. Each intersection corresponds to a threshold probability; that is, a probability level at which a decision maker should consider two courses of action equivalent with respect to expected benefit for the patient. When the probability of disease in a patient exceeds a given threshold, one action is preferable, whereas when the probability of disease falls below the threshold, an alternate action is preferable. This threshold concept is readily illustrated by reference to the figure. The lines denoting the expected utility of discontinuing anticoagulant therapy and of carrying out pulmonary arteriorgraphy intersect at a prior probability of 0.5 (vertical dotted line on left), thus defining a lower threshold of 0.5. The lines denoting the expected utility of carrying out arteriography and continuing anticoagulant therapy intersect at a prior probability of 0.9 (vertical dotted line on the right), denoting an upper threshold of 0.9. Thus, for prior probabilities below the lower threshold, anticoagulants should not be given, and arteriography should not be carried out. For prior probabilities above the upper threshold, anticoagulants should be given without carrying out the diagnostic study. For prior probabilities between the two thresholds, pulmonary arteriography is the optimal choice.*

The sensitivity analysis on the prior probability is readily carried out with reference to these two thresholds. Although, as acknowledged earlier, the prior probability was taken to be 0.7, the four physicians directly involved in the care of this patient considered the lowest reasonable estimate of the prior probability to be 0.6 and the highest reasonable estimate to be 0.85. By reference to Fig. 4 it is evident that both of these limits of the prior probability (0.6 and 0.85) define the same course of action: both lie between the lower and the upper thresholds and therefore both imply that the optimal course of action is to carry out pulmonary arteriography. Thus, the decision would have been insensitive to the prior probability, if no additional diagnostic information was available.

Impact of the Lung Scan on the Decision

With the exception of studies done as part of a properly designed clinical investigation, diag-

*The intersection at which the "discontinue anticoagulant therapy" and "continue anticoagulant therapy" lines cross (the threshold probability of 0.8) is the point above which anticoagulation should be given if no further diagnostic information (e.g., pulmonary arteriogram or lung scan) were available (i.e., the therapeutic threshold[18]). However, because further studies are available, this threshold has little significance.

Table 3. The Effect of the Lung Scan on the Likelihood of Pulmonary Emboli*

Scan Interpretation	Estimated Likelihood Ratio	Revised Probability of Emboli	Action
No. 1. Strongly positive: lobar defect as well as segmental defects in areas where chest x-ray is normal	8	0.95	Continue anticoagulant therapy
No. 2. Weakly positive: segmental defects in areas in which chest film shows failure	2	0.85	Carry out pulmonary arteriogram
No. 3. Negative: normal perfusion	0	0	Discontinue anticoagulation; no pulmonary arteriogram

*Prior probability = 0.7.

nostic tests should be performed only if the result of the study will influence later decision making. If, for example, the diagnosis of pulmonary embolism is virtually excluded on clinical grounds, the results of a lung scan are irrelevant. An evaluation designed to determine prospectively whether or not to carry out a diagnostic test is illustrated here for a lung scan in this patient.

Two key elements characterize a diagnostic test: the information content of the test and the risk of performing the test. For lung scans, the risks are so minimal that they need not be considered. The information content of the test is a function of the frequency of FP and FN results. The information content can be summarized as a single variable, the likelihood ratio, defined for a lung scan as the probability of a given result in patients with documented pulmonary emboli divided by the probability of the same result in patients proved not to have pulmonary emboli.

A lung scan carried out in this patient might have multiple results, but for purposes of illustrating the possible impact of the study we will consider only three: a scan strongly suggestive of pulmonary embolism, a scan not consistent with pulmonary embolism, and a scan showing diffuse perfusion abnormalities consistent with either cardiac failure or pulmonary embolism. The implications of such scans are shown in Table 3. In this table, each radiographic interpretation is accompanied by an estimated likelihood ratio provided by a radiologist using the technique described by Patton.[19]

Calculations of the posterior probability of pulmonary emboli using these data show clearly that the lung scan result *does* have a critical effect on the decision-making process. If strongly positive (interpretation no. 1) and if the likelihood ratio is estimated at 8, the revised probability of pulmonary emboli would be 0.95*, and the optimal decision (Fig. 4) would be to continue anticoagulant therapy. If the scan showed segmental defects only in areas in which the chest x-ray shows pulmonary congestion (interpretation no. 2) and if the likelihood ratio is estimated at 2, the revised probability would be 0.85, and the optimal decision (Fig. 4) would be to perform the arteriogram. If the scan were negative (interpretation no. 3) and if the likelihood ratio was taken to be 0.0,† the revised probability of emboli would be 0.0, and the optimal course would be to discontinue anticoagulant therapy. In fact, the result of the scan in this patient was identical with the first interpretation in Table 3 (strongly positive), and because the likelihood of pulmonary emboli became greater than the therapeutic threshold value of 0.9, pulmonary arteriography was no longer deemed the optimal choice; arteriography was not carried out, and management consisted of continued anticoagulant therapy.

It should be noted, of course, that the intuitive estimation of likelihood ratios may be fraught with error and that in some instances it may be preferable to assess the information content of individual tests by FP and FN rates and to use a slightly different form of Bayes' Rule.

*The revised probability of pulmonary emboli is calculated according to Bayes' rule[19] as follows:

$$\text{Posterior probability} = \frac{1}{\dfrac{(0.3)}{(0.7 \times 8)} + 1} = 0.95$$

†For various reasons, this estimate may be too low; even if the correct value is as high as 0.4; however, the optimal choice for this patient would remain unchanged.

Analysis of the Morbidity and Mortality Assessments

In the previous sections we examined the impact of various estimates of the prior and the posterior probability of emboli as dictated by the possible results of a lung scan. We now carry out another sensitivity analysis and examine the impact on the decision of variations in the estimated morbidity and mortality of anticoagulation and of pulmonary arteriography.

If the excess annual morbidity rate of anticoagulation is taken to be 0.0 and the excess morbidity rate is taken to be only 0.05, recalculation of expected utility shows that pulmonary arteriography is not justified when the mortality rate from this procedure is 5%. In fact, this decision is obvious because the risk of the test would exceed the risk of the treatment. However, if the mortality and morbidity rates of anticoagulant therapy are those used in our example (i.e., 0.05 and 0.2, respectively), and if the mortality rate of pulmonary angiography is taken to be only 1%, recalculation of expected utility shows that a pulmonary arteriogram is the optimal choice if the probability of emboli is between 0.34 and 0.92 (as compared to the range of 0.51 and 0.91 for the original assumptions). Given this lower mortality figure for the test, it is apparent that the actions taken after consideration of the results of the lung scan findings would be the same as those shown in Table 3. Thus, in this patient the decision is insensitive to any mortality rate of pulmonary arteriography between 1% and 5%.

If, however, the lowest reasonable estimates are taken in this patient for all three rates (i.e., mortality and morbidity rates of anticoagulation of 0.0 and 0.05, respectively, and a mortality rate for pulmonary arteriography of 1%), then pulmonary arteriography is the optimal choice if the probability of emboli is between 0.15 and 0.45. In this situation the scan also has a major impact on the decision whether or not to continue anticoagulant therapy or to carry out pulmonary arteriography. The scan, if strongly or moderately positive, makes anticoagulation without pulmonary arteriography the optimal choice, but if the scan shows normal perfusion, then withholding anticoagulant therapy is the best choice. This pattern should be quite familiar to physicians who have dealt with sick cardiac patients suspected of having pulmonary emboli.

Finally, it is instructive to assess the impact on the decision of disregarding the morbidity rates and considering only the mortality data to assign utilities. To carry out this calculation, it is necessary only to substitute the data for life expectancy shown in Table 2 for the utilities shown in Fig. 3. Making this calculation, it is evident first that the decision remains as before (i.e., to carry out the arteriogram); second, that the decision remains the same for prior probabilities between 0.33 and 0.83; and third, that the lung scan has the same influence on the decision as shown in Table 3. Thus, the decision is also insensitive to the elimination of morbidity characteristics in the utility assignments.

The Utility Assessments

A variety of methods have been used to assess utilities. In the patient described above, utilities were estimated without the involvement of the patient, using values for life expectancy and expected time free of morbidity. In some earlier reports describing the technique of decision analysis, utilities were given arbitrary numerical assignments.[3,4] Still others have used monetary assessments,[20,21] and a few investigators have incorporated the view of the patient in the development of such values.[6,7]

In the process of creating a series of utilities, it is often necessary to consider only a single dimension, such as survival or morbidity.[18] Even when such unidimensional scales are used, different measures can be applied; for example, survival can be measured as the percent of patients alive in the near term or over 5 or 10 yr, or it can be represented as life expectancy. If more than one attribute is to be considered (as was done in the patient described here), then some means must be established for combining the separate measures of worth into a single multidimensional utility, which represents, on a single consistent scale, the relative value of the various potential outcomes. With certain restrictions, rather simple means can be used for combining attributes.[22] In the patient described here, two attributes (freedom from morbidity, m, and survival, s) were used initially, although as shown above, the decision was subsequently found to be insensitive to the morbidity data. These two attributes were combined in the form $k_s u(s) + k_m u(m) + k_{sm} u(s)u(m)$, where $u(s)$ is the unidimensional form for utility of survival and $u(m)$ is the unidimensional form for utility of freedom from morbidity. The weighting coefficients k_s, k_m, and k_{sm} establish the relative importance of survival alone, freedom from morbidity alone, and the two combined. In this patient, k_s and k_m were set to 0, and k_{sm} was set to 40. Techniques for fostering patient participation in the assessment of utilities, including the relative importance of survival and freedom from disability are described elsewhere.[6,22]

Obviously, we were quite arbitrary in truncating our original decision tree at the point where the diagnosis and therapy were established. The tree might have been carried further to the right to denote explicitly the possible outcomes in this patient (e.g., intracerebral bleeding after 6 mo of therapy). Indeed, we can view the expected utility of each branch of the tree as a summarization of a potential tree that might extend further to the right. For example, in Fig. 3 the expected utility of node C-1 can be viewed as a summary of the upper half of the tree in the same way that the utility of 290 summarizes the consequences of treated pulmonary emboli in a patient who has not been subjected to pulmonary arteriography. The prognostic implications of expected utilities are discussed elsewhere.[4]

DECISION MAKING: IMPLICIT VERSUS EXPLICIT

Clinical decisions are often made with uncertain and incomplete information. It is sometimes possible to improve the quality of the information upon which such decisions are made by gathering more diagnostic data, but often those data must be gathered at some risk to the patient and certainly at some financial cost. The technique of decision analysis can provide the clinician with a logical structure for making complex clinical decisions. The basic principle of this analysis is to decompose a complex problem into a series of simpler problems or questions that can be answered with reasonable accuracy and which might be answered by information derived from diverse sources, such as the medical literature, consultants, and, on occasion, even the patient. Decision analysis makes it possible to combine data from these separate sources and make a logical choice that optimizes the chance for a good outcome.

One of the major problems with the approach is the very need to be explicit; it is easier not to admit our lack of knowledge in areas where our decisions are affecting patients' lives. But we must recognize that our implicit decisions, our diagnostic algorithms and flow charts, and our "knee-jerk" responses based on clinical experience must include consideration of the same factors that decision analysis requires us to consider explicitly. If our data base is inadequate for explicit decision making, why should it be adequate for implicit decision making? Indeed, isn't it better to state what information should be required and if the data are lacking, then to design studies to gather such critical data?

But what of our patients of today? Studies designed to acquire a better data base will not be completed in time to use the data in the process of making the decisions which affect their lives. The best that can be done is to carefully structure the problem and make our best estimates of the unknown quantities. Indeed, it may be the nature and accuracy of these estimates that represent one important index of our true skill as physicians. After all, what we try to do day by day is to tailor our knowledge and experience to each of our patients. It is this skill that allows us to adapt our past experience to make it appropriate for each patient, since no two patients are exactly alike. Decision analysis should make this process easier in some ways—it lends structure to the process, it pinpoints areas of disagreement, and it helps avoid certain common errors of omission and misinterpretation that plague all human reasoning.[23]

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