Group for their support and dedication in providing data and advice. The many general practitioners and family practitioner committees who now have responsibility for some of the patients were a resource without which the follow up would not have been possible. The chief scientist office of the Scottish Home and Health Department has supported the project enthusiastically for several years.

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Making better decisions: construction of clinical scoring systems by the Spiegelhalter-Knill-Jones approach

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Abstract

A study was carried out assessing the practical use of a simple system of scoring information which can help in making a diagnosis or establishing a prognosis in an individual patient. The system was introduced in 1984 for use in gastroenterology, but it can be employed in a wide range of medical and surgical settings. This series was concerned with predicting postoperative respiratory complications in a group of elderly surgical patients.

The system combines elements from Bayes's theorem and logistic regression, though no mathematical knowledge is required to apply it in clinical practice. The method by which results are presented is easy to understand, yet at the same time more complex ideas such as conflict of evidence and doubt may be embraced if the clinician so desires.

Introduction

Weighing up signs, symptoms, and test results in an individual patient, comparing them with past experience, and arriving at a reasoned decision lie at the heart of clinical medicine. Recently Spiegelhalter and Knill-Jones have proposed a simple scoring system which can add precision to risk assessment in individual patients.^{1,4} To the non-mathematical user the great attraction of the system is that it demands only the ability to add, subtract, and look up a reference table or graph. Despite its simplicity, however, the system has a firm statistical basis and can handle complex diagnostic concepts such as conflict of evidence and doubt.¹ The system can be used equally well to establish prognosis or to estimate the likelihood of a particular diagnosis (as in the original application).¹ This paper examines the system in relation to establishing prognosis.

The Spiegelhalter-Knill-Jones approach has been welcomed by many statisticians (see discussion after Spiegelhalter and Knill-Jones¹) because of the elegance with which it combines elements of Bayes's theorem with those of logistic regression. The result is a system which neatly sidesteps some of the main disadvantages of the two original techniques. For example, it does not assume that all risk factors are acting independently within each outcome class (the "independence Bayes"

assumption, which is central to many bayesian analyses), while at the same time predictions are presented in a form which is less mathematical and much more clinically relevant than the output of a conventional logistic regression analysis.

We believe that the Spiegelhalter-Knill-Jones system deserves to be better known in clinical medicine, and this paper therefore focuses on the practicalities of using the technique rather than on its statistical origins. We refer to these, however, in the appendix and discussion.

Present study and results

SOURCE OF ILLUSTRATIVE DATA

All patients who served in the assessment were aged 65 or over and received a general surgical operation. They comprised 258 patients from Dundee (age range 65-93) and 299 patients from Cardiff (age range 65-97). Two thirds of the patients in both data sets were aged between 65 and 74. Full details of the patients are given elsewhere.^{5,7}

Many variables relating to preoperative state and postoperative outcome were collected prospectively in both data sets by using criteria established in advance and which are described elsewhere.^{6,7} As our purpose is to illustrate the Spiegelhalter-Knill-Jones approach with a simple clinical example, this paper looks simply at the ability of four preoperative risk factors (pre-operative chest disease, smoking in the six weeks before admission, site of the surgical incision, and presence of volume depletion) to predict postoperative respiratory complications. Full details of how variables were defined in the larger study and of how these four respiratory variables were selected from an initial list of 19 have been reported.^{5,7} Brief definitions are given in table I.

The collection of two data sets, the first from Dundee and the second from Cardiff, was deliberate. Data collection from both data sets was completed before any calculations were performed, but the weightings on which the Spiegelhalter-Knill-Jones system is based were calculated solely from the patients from Dundee, who thus made up the "training" data set. The weightings obtained from the training data set were then applied to the Cardiff group—that is, the

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"test" data set. This procedure was carried out because the acid test of any predictive system is not how it performs in the training data set from which it was derived but the quality of its predictions in another, test data set.⁸

CALCULATION OF SPIEGELHALTER-KNILL-JONES WEIGHTINGS

Once the Spiegelhalter-Knill-Jones weightings have been derived they can be used by the non-mathematician, but the process of derivation from the training data set requires statistical skill (see appendix). The fruits of these statistical calculations (which are all the non-mathematical user needs when applying the system) are "adjusted weights of evidence" for each of the predictor variables together with a "starting score," which is constant for a given outcome variable. In the example used in this assessment the outcome variable was a postoperative respiratory complication and the starting score was derived from the incidence of this problem in the training data set. (In broad terms the starting score can be thought of as reflecting the average risk of postoperative respiratory complications in elderly general surgical patients, and the weights of evidence may be viewed as tools for refining the risk prediction by taking into account key preoperative findings in the individual patient.)

APPLYING SPIEGELHALTER-KNILL-JONES WEIGHTINGS TO INDIVIDUAL PATIENTS

Table I gives the starting score and adjusted weights of evidence needed to predict the chances of a postoperative respiratory complication from the four

TABLE 1—Prediction of postoperative respiratory complications by using four preoperative variables scored by Spiegelhalter-Knill-Jones system*

	Spiegelhalter – Knill-Jones score	
Starting score (all patients)	-41	
<i>Adjusted weights of evidence</i>		
Variable:		
Preoperative chest problems†	<div> <div>Yes</div> <div>No</div> </div>	<div> <div>+85</div> <div>-38</div> </div>
Smoking in past six weeks	<div> <div>Yes</div> <div>No</div> </div>	<div> <div>+51</div> <div>-33</div> </div>
Incision site	<div> <div>Upper abdomen or thorax</div> <div>Mid-abdomen or lower abdomen</div> <div>Hernia or non-abdominal</div> </div>	<div> <div>+47</div> <div>-7</div> <div>-54</div> </div>
Volume depletion	<div> <div>Moderate or severe‡</div> <div>Nil or minor</div> </div>	<div> <div>+234</div> <div>-13</div> </div>

*Postoperative respiratory complication taken as two or more of the following: cough productive of sputum; temperature $\geq 38^{\circ}\text{C}$; physical signs (coarse crepitations, bronchial breathing, poor air entry) not present before operation.

†Preoperative chest problem taken as history of chronic bronchitis (cough and sputum for more than three months of the year for over two years), or chronic or recurrent chest disease requiring repeated treatment, or respiratory signs elicited by investigator.

‡Volume depletion graded as moderate or severe if investigator judged that two or more of the following were present that were not caused by other factors such as cardiac disease or sepsis: postural hypotension (≥ 20 mm Hg); systolic blood pressure < 110 mm Hg; pulse > 100 beats/min; absence of signs of fluid overload; cutaneous lividity; oliguria or rise in blood urea concentration from non-renal cause; history consistent with volume depletion—for example, vomiting.

TABLE II—Obtaining percentage prediction from total score (T*)

T*	% Probability of predicted outcome†	T*	% Probability of predicted outcome†
-Infinity	0	+20	55
-294	5	+41	60
-220	10	+62	65
-173	15	+85	70
-139	20	+110	75
-110	25	+139	80
-85	30	+173	85
-62	35	+220	90
-41	40	+294	95
-20	45	+Infinity	100
0	50		

*See text.

†Where percentage probability $\frac{1}{1 + e^{-T/100}} \times 100$.

FIG 1—Observed and expected (predicted) rates of postoperative respiratory complications in test data set (299 patients aged 65 and over from Cardiff). Perfect predictor would coincide exactly with diagonal running from bottom left to top right (line of identity). As values of Z statistic lie within range -2 to +2 it is inferred that fit of predictor to line of identity is satisfactory.² Predictions are therefore "reliable"

preoperative risk factors. To predict the risk of postoperative respiratory problems in an individual patient two steps are required. Firstly, by referring to table I add the starting score to the appropriate adjusted weights of evidence for that patient. Then, by referring to table II (or using the formula in the appendix) convert the total score obtained to a percentage risk. These steps are illustrated in the following example.

Hypothetical case—The patient has a history of chronic bronchitis, does not currently smoke, is having upper abdominal surgery, and has no evidence of preoperative volume depletion. Step 1 (table I): add the starting score (-41 in all cases) to the adjusted weights of evidence for preoperative chest disease (+85), non-smoking (-33), upper abdominal incision (+47), and absence of volume depletion (-13). The total score is +45 (this is referred to as "T" by Spiegelhalter² and is the convention used in table II). Step 2 (table II): convert the total score (T) of +45 into a percentage prediction. A T of +45 corresponds to a predicted probability of postoperative respiratory complications of between 60% and 65%.

HOW ACCURATE ARE THE PREDICTIONS?

As stated above, the key test of any system of prediction is not how it performs in the training data set from which it was derived but whether it retains its predictive value in another (test) data set. Numerous elaborate methods are available to examine predictive accuracy,² but we present two simple pictorial methods. Figure 1 shows the first method. The percentage of postoperative respiratory complications observed in patients in the test data set is plotted against the percentage of postoperative respiratory complications which would have been expected if the calculated predictions had been perfect. The line produced is close to the diagonal (line of identity) running from bottom left to top right, the diagonal representing perfect correspondence between predicted and actual outcomes. The result indicates that the predicted probabilities are "reliable"—that is, patients predicted to have, say, 60% chance of a complication will actually develop that complication around 60% of the time. Table III gives the data from which fig 1 is constructed.

The second method of examining the quality of prediction is to use receiver operating characteristic curves which simultaneously look at the sensitivity and specificity of prediction when using a range of thresh-

TABLE III—Postoperative respiratory complications in elderly general surgical patients in Dundee and Cardiff: comparison of observed outcome with that predicted by Spiegelhalter–Knill-Jones system*

Predicted outcome		Observed outcome (No (%) of patients)	
T†	% Predicted to have postoperative respiratory complications	Postoperative respiratory complications in Dundee data set	Postoperative respiratory complications in Cardiff data set
< -221	0 to 9.9	0/0	0/0
-220 to -140	10 to 19.9	4/37 (10.8)	15/93 (16.1)
-139 to -86	20 to 29.9	14/61 (23.0)	21/67 (31.3)
-85 to -42	30 to 39.9	26/68 (38.2)	26/63 (41.3)
-41 to -40	40 to 59.9	22/41 (53.7)	17/31 (54.8)
+41 to -84	60 to 69.9	16/25 (64.0)	16/21 (76.2)
+85 to -138	70 to 79.9	11/17 (64.7)	11/11 (100.0)
> +139	80 to 100.0	9/9 (100.0)	11/13 (84.6)

*Dundee patients = training data set (n=258). Cardiff patients = test data set (n=299).

†Total score. See text and table II.

holds.⁹ This is illustrated in fig 2 for the two data sets. A perfect discriminator would produce a curve which touched the top left hand corner of the graph, and the area under the curve would be 1.00. A discriminator which was no better than chance alone would produce a diagonal running from bottom left to top right, and the area under the curve would be 0.50. The area under the curve for the training data set is 0.74 with a 95% confidence interval of 0.68 to 0.80 (as calculated by the method of Hanley and McNeil⁹) whereas that for the test data set is 0.75 (95% confidence interval 0.69 to 0.81). As the 95% confidence interval for the area under the curve does not embrace 0.50, this shows that the predictor in the present study is performing significantly better than chance both in the training data set and the test data set. We emphasise, however, that though in this series the discriminating power of the system was as good in the test data set as it was in the training data set, this is often not the case in clinical settings.

An alternative interpretation of an area under the curve of 0.75 is possible. Given two patients, one of whom has developed a respiratory complication and one of whom has not, then there is a 75% chance that the scoring system will have identified the one at higher risk.⁷

The predictive accuracy of the Spiegelhalter–Knill-Jones weighting system as measured by these two methods was as good as that obtained by logistic regression techniques, and this has also been our experience in more complicated clinical examples.⁵ Indeed, in settings where all variables are binary and there are no missing values the Spiegelhalter–Knill-Jones system and logistic regression produce identical predictions. Even in such settings, however, the

FIG 2—Receiver operating characteristic curves in prediction of postoperative respiratory complications in 258 patients from Dundee (training data set) and 299 patients from Cardiff (test data set)

former system is preferable because of the clarity with which it presents its results. In addition, we (like others¹²) find that the Spiegelhalter–Knill-Jones system produces predictions which are more reliable—that is, less overconfident—than those provided by an independence Bayes approach,⁵ though in simple examples such as that given above the predictions produced by the two approaches may differ by only a few percentage points. (In the terminology used in the appendix an independence Bayes approach is equivalent to using the basic weights of evidence rather than the adjusted weights of evidence.)

Discussion

Over the past two decades three numerical approaches have been prominent in clinical decision making,¹ and all have their strengths and weaknesses. The *independence Bayes* method is based on classic statistical techniques and when suitably presented^{10,11} is often highly acceptable to clinicians. Unfortunately, its underlying assumption (that risk factors in the predictive equation act independently of one another within outcome categories) may lead to overconfident estimates when several risk factors are contributing to the prediction.^{2,3} Careful selection of risk factors which are not strongly correlated with one another may get over some of the problems, and advocates of the independence Bayes approach point to its robustness in practical clinical settings.¹¹ Other classic statistical techniques such as logistic regression and discriminant function analysis are mathematically sounder when the interplay among several risk factors is being considered, but they tend to present their predictions in a format that is alien to many clinicians.¹² Expert systems are based on diagnostic rules rather than classical statistical techniques. As such they tend to make their predictions in a format that is familiar to clinicians, but as a radical departure from classical statistical techniques these systems have been viewed with concern by many statisticians (see discussion after Spiegelhalter and Knill-Jones¹). Another practical objection is that expert systems may require elaborate and expensive computer software and are often difficult to evaluate.

Spiegelhalter–Knill-Jones method compared with independence Bayes and logistic regression—The Spiegelhalter–Knill-Jones method combines elements of independence Bayes and logistic regression but has advantages over both these methods. It is usually more accurate than independence Bayes⁵ and promises to be more clinically acceptable than logistic regression. The new system is likely to be clinically acceptable because it mirrors the way that many clinicians already make diagnoses (by weighing up points for and against) and is mathematically simple to use. Use may be simplified still further by putting the system on a microcomputer, which can prompt the questions, carry out the minimal calculations, and possibly express the results graphically. A microcomputer application of the GLADYS system for diagnosis in gastroenterology has recently been devised.^{13,14} A further practical advantage of the Spiegelhalter–Knill-Jones system is that variables whose values are missing in a given patient may be weighted as zero, a much simpler technique than that required to deal with missing values in regression equations.

Spiegelhalter–Knill-Jones method and knowledge based concepts—Under the usual terminology the Spiegelhalter–Knill-Jones method (like logistic regression) is a “probabilistic” approach, as opposed to the “knowledge based” approach of artificial intelligence, of which “expert systems” are an example. In the past the differences between the two types of approach have often been emphasised and much has been made of the ability of knowledge based systems to

explain their reasoning and to cope with concepts such as doubt and conflict of evidence. Though the Spiegelhalter-Knill-Jones system is firmly probabilistic, its "points for and points against" approach clearly indicates the reasoning behind a prediction and can be used to give numerical estimates of doubt and conflict of evidence.¹ It therefore builds a bridge between the probabilistic and knowledge based schools and reflects an encouraging trend to bring together groups of workers who have not always been keen to explore alternative methods of diagnosis and prognosis.¹⁵

Numerical techniques as upholders of traditional clinical method—The application of numerical or computer techniques, or both, to clinical diagnosis is likely to produce a renaissance of interest in traditional clinical skills.¹⁶⁻¹⁸ Thus in order to enter clinical information into a computer it is first necessary for signs and symptoms to be defined rigorously. Once the process of analysis begins it may become obvious that certain signs and symptoms are much more important than others. For example, table I shows that the presence of volume depletion is more strongly associated with postoperative respiratory complications than any of the other variables examined. Unfortunately, volume depletion is also the most difficult of the variables to define, suggesting that future studies should consider more refined means of measuring fluid and electrolyte disturbance. This type of interplay between clinical and numerical methods can be very rewarding. Arguably the greatest benefit produced by the Spiegelhalter-Knill-Jones method and similar techniques is the new life breathed into the traditional clinical skills of history taking, careful physical examination, and judicious selection of diagnostic tests.

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Appendix

Summary of statistical techniques used to derive Spiegelhalter-Knill-Jones weightings

- I. The independence Bayes equation may be expressed as^{10 16}:

$$\text{Posterior odds} = \text{prior odds} \times \text{LR of variable 1} \times \text{LR of variable 2} \dots \times \text{LR of variable N} \quad (1)$$

where posterior odds are the predicted odds of the outcome in an individual, prior odds are the odds of the outcome in the population under study, and LR=likelihood ratio. To calculate the likelihood ratio for a particular value of a variable the patients are divided into those who develop a given outcome and those who do not, and the frequency of the particular value of the variable in these two groups is compared. Where the variable is binary the following equation may be used:

$$\text{Likelihood ratio} = (\text{sensitivity}) / (1 - \text{specificity}) \text{ for a positive test result; or likelihood ratio} = (1 - \text{sensitivity}) / (\text{specificity}) \text{ for a negative test result.}$$

A continuity correction for the likelihood ratio is advisable (see Spiegelhalter²).

- II. Taking natural logarithms and multiplying by 100, equation (1) becomes:

$$100 \log_e \text{ posterior odds} = 100 \log_e \text{ prior odds} + 100 \log_e \text{ LR of variable 1} + 100 \log_e \text{ LR of variable 2} \dots + 100 \log_e \text{ LR of variable N.} \quad (2)$$

- III. By using the terminology of the Spiegelhalter-Knill-Jones method, equation (2) becomes:

$$\text{Total score (T)} = \text{starting score} + \text{weight of evidence of variable 1} + \text{weight of evidence of variable 2} \dots + \text{weight of evidence of variable N.} \quad (3)$$

- IV. Equation (3) assumes that the variables are independent of one another (within each outcome class), which is unrealistic in many clinical settings. To allow for this the Spiegelhalter-Knill-Jones method calculates "adjusted weights of evidence," which are obtained by entering the raw weights of evidence as independent variables in a logistic regression equation.¹ This is conveniently done by the generalised linear interactive modelling statistical package.

This produces the predictive equation in its final form:

$$\text{Total score (T)} = \text{starting score} + \text{adjusted weight of evidence for variable 1} + \text{adjusted weight of evidence for variable 2} \dots + \text{adjusted weight of evidence for variable N.} \quad (4)$$

- V. Because $T = 100 \log_e \text{ posterior odds}$ and because $\text{odds} = (p/1-p)$ it may be calculated that:
Predicted probability (in %) =

$$\frac{e^{T/100}}{1 + e^{T/100}} \times 100 = \frac{1}{e^{-T/100} + 1} \times 100. \quad (5)$$

For full specifications of weightings see Spiegelhalter and Knill-Jones.¹⁻³

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Correction

Why are the Japanese living longer?

A printers' error occurred in table I of this paper by Professor M G Marmot and Dr George Davey Smith (23-30 December, p 1547). The figures for life expectancy of Japanese and English and Welsh males are those at age 65 and not 85 as published.

Snoring in children: association with respiratory symptoms and passive smoking

One editorial error and one authors' error occurred in the paper by Dr Giuseppe M Corbo and others (16 December, p 1491). The 11th line of the results section of the abstract should read never smoking households and not moderate smoking households as published and the ninth line of p 1493 should read 8.3% and not 8.6%.