Elective surgery for asymptomatic, unruptured, intracranial aneurysms: a cost-effectiveness analysis

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Cost-effectiveness analysis uses both economic and clinical outcomes data to evaluate treatment options. In this era of economic constraints on health care, treatments that are not cost-effective will increasingly be denied public and private insurance reimbursement. The authors used mathematical modeling techniques to assess the cost-effectiveness of elective surgery for the treatment of asymptomatic, unruptured, intracranial aneurysms. Input values for the Markov model used in this study were determined from both the literature and clinical judgment. Direct medical costs for hospitalization and physician fees were derived from Medicare cost reports and resource-based relative-value units, expressed in 1992 U.S. dollars. Costs and benefits were discounted at an annual rate of 5%.

Using baseline model assumptions for a 50-year-old patient, elective aneurysm surgery provides an average of 0.88 additional quality-adjusted life years (QALYs) compared with nonsurgical treatment. However, prompt elective surgery ($23,300) costs more than expectant management ($2100), in which only patients whose aneurysms rupture incur treatment costs. Combining the outcomes and cost data, the incremental cost-effectiveness of elective aneurysm surgery is $24,200 per QALY, which is comparable to other accepted medical or surgical interventions, such as total knee arthroplasty ($15,200/QALY) or antihypertensive therapy in a 50-year-old patient ($29,800/QALY).

Prompt elective surgery for asymptomatic, unruptured, intracranial aneurysms is recommended as a cost-effective use of medical resources provided: 1) surgical morbidity and mortality remain at reported levels; 2) the patient has a life expectancy of at least 13 additional years; and 3) the patient experiences a decrease in quality of life from knowingly living with an unruptured aneurysm.

KEY WORDS • unruptured aneurysm • cost-effectiveness analysis • medical economics • decision analysis • Markov model

Aneurysms allow us to estimate the prevalence of intracranial aneurysms at 0.2% to 8.9%. Each year 28,000 people in the United States will suffer aneurysmal subarachnoid hemorrhage (SAH), yet most aneurysms remain asymptomatic. Asymptomatic, unruptured, intracranial aneurysms come to the attention of neurosurgeons after SAH in a patient with multiple aneurysms or during the investigation of spurious phenomena (for example, magnetic resonance imaging for headaches). In the past, given the low annual rate of hemorrhage and the risks of surgery, neurosurgeons have recommended expectant management, with surgery at a later date if the aneurysm ruptures or becomes symptomatic. Since the development of present anesthetic and microsurgical techniques, most neurosurgeons advocate prompt elective surgical repair of asymptomatic, unruptured, intracranial aneurysms. The superiority of elective aneurysm surgery has not been tested in any prospective clinical trials, although decision analysis models show more favorable outcomes with surgery than with expectant management. Society and physicians are increasingly aware of the economic implications of treatment decisions. Cost-effectiveness analysis is a technique that uses both economic and clinical outcomes data to evaluate treatment options. In this era of economic constraints on health care, treatments that are not cost-effective will increasingly be denied public and private insurance reimbursement. The present report compares the cost-effectiveness of prompt elective surgery versus expectant management for the treatment of asymptomatic, unruptured, intracranial aneurysms.

Clinical Material and Methods

The Model

Mathematical modeling techniques allow us to analyze complex problems in an idealized fashion. Although some simplification is inevitable, modeling has the advantage of...
offering a quantitative examination of the problem. In cost-effectiveness analysis, the model incorporates both known and estimated data on outcomes, probabilities, and costs related to the clinical problem and treatment options under consideration. We developed a Markov model to evaluate the outcomes of prompt elective surgery for all patients versus expectant management, in which surgery is performed only when patients suffer an SAH. The model is defined by a set number of discrete states (for example, perioperative death, survival with normal neurological function after elective surgical repair of an asymptomatic, unruptured, intracranial aneurysm). Each state has an assigned quality of life value and an associated direct medical cost. Transitions between states may occur during each yearly cycle and occur on average at the midpoint of the cycle. Our analysis will continue until all individuals in the hypothetical cohort die from their aneurysm or natural causes. Patients with decreased life expectancies are also analyzed.

In our model, surgery is the only treatment modality and is assumed to remove permanently the risk of SAH from the repaired aneurysm. Endovascular techniques are being developed for the treatment of intracranial aneurysms, but their role has yet to be established, and they will not be considered in this study. Patients who choose prompt elective surgery either: 1) die perioperatively; 2) survive with a neurological deficit and a repaired aneurysm; or 3) survive with normal neurological function and a repaired aneurysm. In succeeding years, survivors live with their postoperative level of functioning until they die from causes other than aneurysmal SAH.

Patients who opt for expectant management knowingly live with an asymptomatic, unruptured, intracranial aneurysm and may die from causes other than aneurysmal SAH. Alternatively, they may develop aneurysmal SAH. The probability of hemorrhage from an unruptured intracranial aneurysm is approximately 1% per year, with estimates ranging from 0.2% to 5% per year. There is evidence that larger aneurysms are more prone to hemorrhage and that aneurysms less than 10 mm in diameter are unlikely to rupture.

Prehospitalization Death After SAH. An epidemiological population-based study conducted in Rochester, Minnesota, found that 12% of patients with SAH die before receiving medical care.

Morbidity and Mortality From Aneurysmal SAH. Data from the International Cooperative Study on the Timing of Aneurysm Surgery were used to estimate outcomes from aneurysm bleeding. At 6 months after SAH, the 3521 hospitalized patients had a combined 26% mortality, 16% morbidity, and 58% complete recovery. Because younger patients had better outcomes after SAH than older patients, we used outcome data stratified by age in the model.

Risks From Elective Aneurysm Surgery. A recent review and metaanalysis of 28 separate articles reporting the results of elective surgery for unruptured, asymptomatic aneurysms in 733 patients found a morbidity rate of 4.1% (95% confidence interval (CI): 2.8, 5.8%) and a mortality rate of 1% (95% CI: 0.4, 2.0%). Using the limited data available in the 28 articles, there was insufficient statistical power to associate potential risk factors such as age, sex, aneurysm size, or aneurysm location with increased surgical morbidity or mortality. Consequently, in our model all aneurysm patients have similar surgical outcomes.

Morbidity and Mortality From Causes Other Than SAH. We determined annual probability of death from all causes using age-stratified National Center for Health Statistics life tables. We used the declining exponential approximation of life expectancy when we modeled decreased life expectancy from comorbid disease. All morbidity was assumed to come from the sequelae of SAH or surgery.

Quality-Adjusted Survival

Neurosurgical disease and treatment can have a significant impact on patient quality of life; thus, we expressed the outcome from each treatment strategy as the expected length of survival adjusted for quality, and referred to it as quality-adjusted life years (QALYs). To establish expected QALYs, we identified a value or ‘QALY weight’ score between 0.00 and 1.00 for each of the different states in the model. The QALY weight represents the portion of a healthy year that is equivalent to living a full year in the less-valued state. Lifetime QALYs equal the sum of the number of years in each state multiplied by the QALY weight associated with the state.

Knowingly Living With an Asymptomatic, Unruptured, Intracranial Aneurysm. Clinical experience indicates that knowingly living with an unruptured intracranial aneurysm reduces the quality of life for most patients, but there are no published studies quantifying the quality of life of knowingly living with an aneurysm. After considering the impact of psychological distress on quality of life as measured by several scales and consulting with neurosurgeons at the University of Pennsylvania, we assigned a value of 0.95 to living with an asymptomatic, unruptured, intracranial aneurysm. The selection of a high value minimizes the impact the aneurysm has on a patient’s life, and favors expectant management.

Postoperative Recovery Period. Based on clinical experience we assigned all patients who undergo surgery a 3-month postoperative recovery period. During this time we assume a quality of life value equal to 75% of the eventual long-term value.

Death. By convention, death is assigned a value of zero.

Postoperative or Post-SAH Deficit. Several methods exist to measure the quality of life after stroke. Previous
Cost-effectiveness of elective aneurysm surgery

work in neurosurgical decision analysis estimated the value of living with a neurological deficit at 0.50 to 0.75.23,33,68,72 A study of stroke patients found a 24% reduction in quality of life for long-term survival with a neurological deficit.4 We assumed a value of 0.76 for survival with a postoperative or posthemorrhagic neurological deficit.

Postoperative Normal Function. Normal function is conventionally assigned a value of 1.00.

Treatment Costs

We examined the direct medical costs of treating asymptomatic, unruptured, intracranial aneurysms from the societal perspective. Hospital and physician charges often differ significantly from the actual costs of delivering health care services.22 This difference precludes the use of charge or billing data and necessitates the use of various alternative methods to estimate costs. Mean nationwide Medicare Cost Report data from 1991 (Prospective Payment Assessment Commission, personal communication, 1994) were used to determine the costs of hospitalization. Physician costs were derived from 1992 Medicare resource-based relative-value units.3,32 Rehabilitation and long-term costs were determined for the 1st year after suffering a stroke69 and for each subsequent year.54 All costs are expressed in 1992 U.S. dollars, using the U.S. urban average Consumer Price Index for medical care for cost conversions.2

Each state in the Markov model is associated with one of five cost scenarios: 1) the hospital and physician costs of a nonsurgical stroke admission after SAH (diagnosis-related group (DRG) 14, specific cerebrovascular disorder except transient ischemic attack); 2) the hospital and physician costs for aneurysm surgery, either elective or after SAH (DRG 1; craniotomy at > 17 years of age except for trauma); 3) the rehabilitation and nursing home costs in the 1st year after suffering a stroke;49 4) the annual rehabilitation and nursing home costs in subsequent years after a stroke;54 and 5) zero costs (patients who never bleed from their untreated aneurysm). The estimated cost of a nonsurgical hospital admission for stroke after aneurysmal SAH was $6500, and the estimated costs of an admission for aneurysm surgery was $19,300. The average cost of acute care, rehabilitation, and chronic care for stroke patients in the 1st year after a stroke varied with age from $13,800 to $20,200. After the 1st year, the average annual cost for stroke patients varied with age from $6500 to $16,400.

Discounting and Computation

Benefits and costs are more significant to individuals the sooner they occur. To account for this phenomenon, both benefits and costs can be expressed as present values by discounting future values at the rate of 5% per year.19,25,65 Computational work was performed on a personal computer using commercially available software (Excel Version 4.0; Microsoft Corp., Redmond, WA, and SAS Version 6.04; SAS Institute, Cary, NC).

Cost-Effectiveness Ratios

In this analysis, we report the expected benefits and costs associated with the treatment strategies of prompt elective surgery and expectant management. Treatment strategies that yield greater quality-adjusted survival and are less expensive dominate less effective, more expensive strategies and are the treatment of choice. However, if one strategy yields greater quality-adjusted survival but is also more expensive, further analysis is necessary to determine whether the extra survival justifies the extra expense. This determination is made using the incremental cost-effectiveness ratio, which is calculated as follows: cost-effectiveness = (cost A – cost B)/(effectiveness A – effectiveness B).

Sensitivity and Threshold Analyses

Sensitivity analyses were performed by altering the input value of individual variables within clinically reasonable ranges and assessing the effects on the model conclusions of the uncertainty of the assumptions made in the primary analysis. The ranges of the variables tested included: 1) age (30–70 years); 2) annual probability of SAH from an unruptured intracranial aneurysm (0.2%–5.0%); 3) elective surgical morbidity (2.8%–5.8%); 4) elective surgical mortality (0.4%–2.0%); 5) postoperative recovery period duration (0–6 months); 6) postoperative recovery period function (50%–100% of eventual function); 7) value of living with a neurological deficit (0.50–1.00); 8) value of knowingly living with an asymptomatic, unruptured, intracranial aneurysm (0.90–1.00); and 9) discount rate (0%–10%).

Threshold analysis entails perturbing individual model baseline input values until a model output goal is achieved. Most commonly, the goal is reversal of the original model conclusion favoring a particular treatment option (other goals can also be examined; for example, economic endpoints). The input variable value at which the model output goal is achieved is designated the threshold value. All nine variables listed above were subject to threshold analysis. Additionally, the effect on outcomes of decreased life expectancy from comorbid disease was assessed.

The value of knowingly living with an asymptomatic, unruptured, intracranial aneurysm had a marked impact on our results, which suggested additional exploration of this variable. Consequently, we performed a secondary analysis in which the value of knowingly living with an unruptured aneurysm was set at its maximum of 1.00, and the remaining eight variables were subjected to a secondary sensitivity analysis. Secondary threshold analyses similar to the primary analysis were also performed, again with the value of knowingly living with an unruptured aneurysm set at 1.00.

Results

Cost-Effectiveness of Elective Surgery

Effectiveness. Prompt elective surgery yields a greater number of QALYs compared to expectant management. In the primary analysis (baseline, 50-year-old patients, the mean age of patients undergoing elective aneurysm surgery in our literature review), the strategy of prompt surgery provides an additional 0.88 discounted QALYs. The magnitude of the benefit of prompt surgery over expectant management decreases with the age of the pa-
tient but is still present for patients as old as 70 years of age. We found QALY benefits of 0.95, 0.94, 0.88, 0.75, and 0.56 for patients 30, 40, 50, 60, and 70 years of age, respectively, when comparing prompt elective surgery with expectant management. The cost per QALY was $22,900; $22,800; $24,200; $27,800; and $42,800 for 30-through 70-year-olds, respectively.

**Costs.** The treatment strategy of prompt elective surgery for all patients is more expensive than expectant management. The average cost for patients who undergo prompt elective surgery is $23,300. The average cost for expectant management patients is $2100 (the weighted average of zero cost for patients with unruptured aneurysms and the discounted costs for patients who at some point suffer SAH followed by death, hospitalization, and/or nursing home care).

**Cost-Effectiveness.** Combining the incremental cost and effectiveness data in the primary analysis reveals a cost per QALY of $24,200, which varies with the age of the patient, as discussed above.

**Sensitivity Analyses**

The sensitivity analysis for nine selected model variables is shown in Table 1. The cost per QALY is most influenced by the value of knowingly living with an asymptomatic aneurysm. As patient anxiety increases, quality of life decreases, and elective aneurysmorrhaphy becomes more cost-effective. In the baseline example of a 50-year-old patient with a quality of life value of 0.95, the cost per quality-adjusted life year (QALY) is $24,200. The dotted horizontal line corresponds to the $50,000 per QALY threshold of “cost-effectiveness.” At quality of life values above 0.98, the cost per QALY exceeds the $50,000 threshold.

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### TABLE 1

Results and sensitivity analyses for nine selected model variables

<table>
<thead>
<tr>
<th>Input Variable*</th>
<th>Age (yrs)</th>
<th>Annual Probability of SAH</th>
<th>Elective Surgical Mortality</th>
<th>Postop RP Duration (mos)</th>
<th>Postop RP Function</th>
<th>Value of Living With Neurological Deficit</th>
<th>Value of Knowingly Living With UA</th>
<th>Discount Rate</th>
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* SAH = subarachnoid hemorrhage; UA = unruptured aneurysm; RP = recovery period; QALY = quality-adjusted life year; NA = not applicable. In the primary and secondary analyses, the values of knowingly living with an unruptured aneurysm were 0.95 and 1.00, respectively.
† Prompt elective surgery is both less effective and more expensive.

**Fig. 1.** Graph demonstrating the profound impact on the cost-effectiveness of elective surgery of the anxiety a patient experiences from knowingly living with an asymptomatic aneurysm. As patient anxiety increases, quality of life decreases, and elective aneurysmorrhaphy becomes more cost-effective. In the baseline example of a 50-year-old patient with a quality of life value of 0.95, the cost per quality-adjusted life year (QALY) is $24,200. The dotted horizontal line corresponds to the $50,000 per QALY threshold of “cost-effectiveness.” At quality of life values above 0.98, the cost per QALY exceeds the $50,000 threshold.

The average cost for patients who undergo prompt elective surgery is $23,300. The average cost for expectant management patients is $2100 (the weighted average of zero cost for patients with unruptured aneurysms and the discounted costs for patients who at some point suffer SAH followed by death, hospitalization, and/or nursing home care).

**Cost-Effectiveness.** Combining the incremental cost and effectiveness data in the primary analysis reveals a cost per QALY of $24,200, which varies with the age of the patient, as discussed above.

**Sensitivity Analyses**

The sensitivity analysis for nine selected model variables is shown in Table 1. The cost per QALY is most influenced by the value of knowingly living with an asymptomatic, unruptured, intracranial aneurysm, with less influence shown by the discount rate and the annual probability of SAH from an unruptured aneurysm. Other input variables had relatively little impact on the cost per QALY.

**Value of Knowingly Living With an Asymptomatic, Unruptured, Intracranial Aneurysm.** Figure 1 illustrates the relationship between the value of knowingly living with an asymptomatic, unruptured, intracranial aneurysm and the cost per QALY of elective surgery. The incremental cost-effectiveness ratio varies from $13,700 to $103,200 for values ranging from 0.90 to 1.00. Fifty thousand dollars per QALY has been proposed as a guideline for determining if an intervention is cost-effective.43 Note that extreme values of knowingly living with an unruptured aneurysm push the cost per QALY above this threshold. Given the uncertainty of this variable and its influence on results, we dichotomized the remainder of the study into a
primary analysis where the value was 0.95, and a secondary analysis where the value was 1.00. The secondary analysis shows a cost per QALY of $103,200.

Annual Probability of SAH From an Asymptomatic, Unruptured, Intracranial Aneurysm. The relationship between the annual probability of SAH from an unruptured aneurysm and the cost-effectiveness ratio is demonstrated in Fig. 2 upper left. The cost per quality-adjusted life year (QALY) in the primary analysis is below the $50,000 threshold (horizontal dotted line) at virtually any nonzero bleed rate. In the secondary analysis, the annual hemorrhage rate must be at least 1.4% before the cost of QALY descends below the $50,000 threshold. Upper Right: Cost-effectiveness of elective surgery is directly proportional to the discount rate. The cost per QALY in the primary analysis is below the $50,000 threshold (horizontal dotted line) at any discount rate from 0% to 10%. In the secondary analysis, the discount rate must stay below 2.8% for the cost per QALY to remain below the $50,000 threshold. Lower Left: Cost-effectiveness of elective surgery is inversely related to the elective surgical mortality rate. The cost per QALY is below the $50,000 threshold (horizontal dotted line) for elective surgical mortality rates of less than 2.2% in the primary analysis. In the secondary analysis, elective surgical mortality rates can go no higher than 0.4%, or the cost per QALY exceeds the $50,000 threshold. Lower Right: Cost-effectiveness of elective surgery is directly proportional to patient life expectancy. In the primary analysis, patient life expectancy must exceed 16.2 years before the cost per QALY falls below the $50,000 threshold. In the secondary analysis, no patient has a life expectancy long enough to drop the cost per QALY below the $50,000 threshold.

Cost-effectiveness of elective aneurysm surgery from undefined to $10,100 for annual SAH probabilities ranging from 0.2% to 5%.

Discount Rate. The relationship between the discount and the cost-effectiveness of elective aneurysm surgery is shown in Fig. 2 upper right. The cost per QALY for primary analysis patients varies from $10,100 to $46,100 for discount rates ranging from 1% to 10%. The cost per QALY for secondary analysis patients varies from $22,400 to undefined for discount rates ranging from 0% to 10%.

Threshold Analyses

The two thresholds of concern occur when prompt elec-
 elective surgery is no longer preferred over expectant management, and when the incremental cost-effectiveness ratio of elective surgery exceeds the $50,000 per QALY cost-effectiveness threshold. In the primary threshold analysis, elective surgery is the favored strategy unless: 1) surgical mortality is greater than or equal to 3.9% accompanied by 16% morbidity; 2) the discount rate is more than 211%; or 3) patient life expectancy is less than 5.3 years. The cost per QALY of elective surgery is less than $50,000 unless: 1) surgical mortality is greater than 2.2% accompanied by 9% morbidity; 2) the value of knowing living with an asymptomatic, unruptured, intracranial aneurysm is greater than 0.98; 3) the discount rate is more than 10.8%; or 4) life expectancy is less than 16.2 years.

The secondary threshold analysis reveals that elective surgery is the favored strategy unless: 1) the annual probability of aneurysmal SAH is less than or equal to 0.6%; 2) elective surgery mortality is greater than 1.7% accompanied by 6.9% morbidity; 3) the value of life with a neurological deficit is less than 0.05; 4) the discount rate is more than 9.9%; or 5) patient life expectancy is less than 18.4 years. The cost per QALY of elective surgery is less than $50,000 unless: 1) the annual probability of SAH is less than 1.4%; 2) elective surgery mortality is greater than 0.4% accompanied by 1.7% morbidity; 3) the discount rate is greater than or equal to 2.8%; or 4) patient life expectancy is less than 71 years.

### Discussion

We used mathematical modeling techniques to examine the cost-effectiveness of elective surgery for asymptomatic, unruptured, intracranial aneurysm. In the primary analysis, across a wide range of clinically relevant model assumptions, prompt elective surgery always yields more discounted QALYs than expectant management. Patients only need an expected life span of 5.3 years or more to realize some benefit from prompt elective surgery. Economic considerations broaden the perspective of the analysis beyond simply maximizing the QALY benefit to the patient, by acknowledging that benefits always have a price. It is not surprising that the direct medical costs of prompt elective surgery are greater than expectant management, that is, it is more expensive to operate on all patients now ($23,300 mean cost) than on some patients in the future ($2100 mean cost). The incremental cost-effectiveness ratio relates this higher cost to the benefits of prompt elective surgery. Prompt elective surgery has an incremental cost-effectiveness ratio of $24,200 per QALY. In Table 2 we enumerate the relative cost-effectiveness of elective aneurysm surgery, coronary artery bypass grafting, total knee arthroplasty, balloon angioplasty, and antihypertensive therapy. Note that the cost per QALY of elective aneurysm surgery is comparable to other widely practiced medical and surgical interventions.

### Sensitivity and Threshold Analyses

In the sensitivity analysis, we explored the influence of the assumptions of the model on the cost-effectiveness of elective aneurysm surgery.

**Value of Knowingly Living With an Asymptomatic, Unruptured, Intracranial Aneurysm.** The value of knowing living with an unruptured aneurysm is dependent on numerous factors, including interactions with the treating physicians, fear of the unknown, personal contact with other aneurysm patients, and personal attitude toward risk. It is the clinical experience of practicing neurosurgeons that most patients harbor an unruptured aneurysm with at least mild trepidation. Consequently we believe that the primary analysis, in which patients have a slight devaluation of their quality of life (value 0.95), accurately represents the values and expected outcomes for the majority of aneurysm patients. Unfortunately, no quantitative assessments of the value of knowingly living with an unruptured aneurysm have been published. To address the influence of this variable on the model conclusions, we also undertook a secondary analysis, in which the value of knowingly living with an unruptured aneurysm was assigned the maximum possible value of 1.00 (meaning that an individual’s quality of life is unaffected by the knowledge that they have an unruptured intracranial aneurysm). The contrast between the primary and secondary analysis results highlights the importance of this assumption.

Most information about aneurysms is conveyed by physicians; thus, physicians play a pivotal role in shaping a patient’s attitude toward their aneurysm. For example, a physician who believes that an unruptured intracranial aneurysm is dangerous and warrants surgery will communicate this concern to the patient. This information reduces the value of living with the aneurysm, with a corresponding increase in the cost-effectiveness of elective surgery (Fig. 1). In contrast, a physician who believes that aneurysms are relatively benign, particularly when compared to the risks of elective surgery, will reassure the patient. This reassurance will mitigate the negative impact of the aneurysm on the patient’s quality of life, increase the value of knowingly living with an unruptured aneurysm, and decrease the cost-effectiveness of elective surgery. Our analysis can be viewed as quantifying the effects of the treating physician bias. Alternatively, the
Cost-effectiveness of elective aneurysm surgery

analysis demonstrates the cost of informing an asymptomatic patient that they have an unruptured aneurysm.

**Annual Probability of SAH From Asymptomatic, Unruptured, Intracranial Aneurysms.** The primary analysis is not sensitive to the annual probability of SAH from an unruptured aneurysm; for a wide range of values, elective surgery is cost-effective (Fig. 2 upper left). The untreated annual rupture rate is of significance in the secondary analysis. For individuals who suffer no diminution in quality of life from knowingly living with an unruptured intracranial aneurysm, elective surgery is preferred for rupture rates greater than 0.6%, and cost-effective for rates greater than or equal to 1.4%. The International Study of Unruptured Intracranial Aneurysms is an international effort to collect retrospective and prospective data on the natural history and surgical outcomes of unruptured intracranial aneurysms (unpublished data). Identification of aneurysm and patient characteristics associated with differential spontaneous rupture rates may allow refinement of our decision analysis model.

**Discount Rate.** The discount rate can have a significant impact on an analysis when events of interest occur in the future. Higher discount rates are less favorable toward elective surgery with its early costs (surgical morbidity, mortality, and expense) and delayed benefits (increased quality-adjusted survival). Indeed, a high discount rate can increase the cost-effectiveness ratio or even reverse the model’s conclusions and render expectant management superior to surgery. The primary analysis outcomes are robust to changes in the discount rate; elective surgery is both preferred and cost-effective unless absurd discount rates are used. The secondary analysis outcomes are more sensitive to the discount rate. Whereas the discount rate must be quite high (9.9%) before expectant management is the preferred treatment option (Fig. 2 upper right). The primary analysis outcomes are robust to changes in the discount rate; elective surgery is both preferred and cost-effective unless absurd discount rates are used. The secondary analysis outcomes are more sensitive to the discount rate.

**Operative Risk.** Clinical impressions of the importance of operative risk in the consideration of elective neurosurgery for patients with asymptomatic, unruptured, intracranial aneurysms are confirmed by the primary threshold analysis, in which increasing the elective surgical risk reverses the model’s cost-effectiveness conclusions (Fig. 2 lower left). The elective surgical outcomes values used in our analysis are from a metaanalysis of 28 series containing a total of 733 patients. These data have many potentials sources of patient referral, selection, and reporting bias that may result in an underestimation of operative risk in this pooled sample. Furthermore, the impressively low operative mortality and morbidity data derived from experienced surgeons with highly trained support staff and may not be achieved by less experienced neurosurgeon or medical centers.

There is a growing body of evidence that some hospitals and physicians obtain better outcomes than others for surgical interventions. Given the relationship between operative risk and the cost-effectiveness of elective aneurysm surgery, the identification of these institutions and/or physicians may be a prerequisite for cost-effective elective aneurysm surgery. Otherwise, operative mortality rates may increase to the point at which elective aneurysm surgery is no longer cost-effective, or is even detrimental to the patient.

With an informed understanding of risk factors for adverse outcomes after elective aneurysm surgery, neurosurgeons would be better able to select patients for whom surgery will be beneficial or cost-effective. Neurosurgeons have speculated on the relationship between the risks associated with elective surgery on asymptomatic, unruptured, intracranial aneurysms and such factors as patient age, sex, comorbid disease, or aneurysm size and location. An attempt to stratify elective surgical risk by aneurysm size in 107 patients found no significant differences in outcome (Fisher’s exact test calculated from reported data, p = 0.53, and a published metaanalysis did not find sufficient data to draw any conclusions about the relationship between surgical risk and aneurysm or patient characteristics. The aforementioned International Study of Unruptured Intracranial Aneurysms is presently collecting prospective data on 1200 patients and should afford a better understanding of risk factors for adverse surgical outcomes.

**Life Expectancy.** Neurosurgeons have recognized the importance of considering life expectancy in managing patients with an asymptomatic, unruptured, intracranial aneurysm. The primary threshold analysis provides a quantitative perspective on patients with reduced life expectancies from advanced age or nonaneurysmal disease. Patients need only have a life expectancy of 5.3 years to benefit from elective surgery in the primary analysis, but the cost per QALY is initially exorbitant (Fig. 2 lower right). A patient must survive for 16.2 years before the cost per QALY of prompt elective surgery drops below $50,000 per year. Patients in the secondary analysis with a life expectancy of less than 18.4 years because of advanced age or nonaneurysmal disease will not benefit from and should not have elective aneurysm surgery. Furthermore, the survival threshold for the cost per QALY to drop below $50,000 is greater than 50 years that is, virtually no patient will live long enough for the cost per QALY of elective aneurysm surgery to become reasonable. Thus, patients who are unconcerned about their aneurysm, although they will benefit from prompt elective surgery if they are expected to survive 18.4 years or more, always do so at a cost in excess of $50,000 per QALY.

**Limitations of the Model**

The value of knowingly living with an asymptomatic, unruptured, intracranial aneurysm has a significant impact on the model outputs. Formal assessments of patient preferences are needed to better understand the effects of this knowledge. Patient preferences can also change over time; our model assumed constant patient preferences. There is a growing recognition that patient values and preferences can differ from physician perceptions, and that patient values should be used by clinicians. Although we agree that patient preferences must be incorporated into the clinical decision-making process, they cannot be allowed to overwhelm all other factors. Consider patients with extreme anxiety from knowingly living with an asymptomatic, unruptured, intracranial aneurysm, such that their quality of life is diminished to 0.70. The model shows that elective
surgery on these patients is cost-effective for surgical mortality rates of up to 11% accompanied by a 46% stroke rate. Many surgeons would be reluctant to undertake such an operation. Perhaps society will agree upon normative limits beyond which extreme patient preferences will not be used in clinical decision making.

An important component of our model is the assumption of similar natural histories and surgical results for all patients with asymptomatic, unruptured, intracranial aneurysms. Whereas no reasonable neurosurgeon believes that all unruptured aneurysms have the same natural history or surgical risks, at present there is inadequate data in the literature on the effects of aneurysm size, location, or patient age, sex, or associated medical conditions on the natural history and surgical results of asymptomatic, unruptured, intracranial aneurysms. The International Study of Unruptured Intracranial Aneurysms will help address this deficiency. We plan to modify our model as more data become available.

All methods of estimating costs are fraught with difficulties, and our use of European rehabilitation costs after stroke and Medicare prospective reimbursements for hospitals and physician acute care is no exception. Doubtless post-SAH surgical patients consume more resources than do postselective surgery patients, but present prospective reimbursements schemes do not allow differentiation between elective aneurysm surgery and surgery following emergency admission for SAH. Our use of similar cost estimates for elective and post-SAH surgery likely favors expectant management because it overestimates the cost of elective aneurysm surgery relative to post-SAH surgery.

Conclusions

We used cost-effectiveness analysis to compare prompt elective surgery to expectant management for the treatment of asymptomatic, unruptured, intracranial aneurysms. Prompt elective surgery increases the duration and quality of survival compared to expectant management. This effect persists despite varying the underlying assumptions across a wide range of values. Expectant management becomes the preferred strategy only if the patient’s anticipated life span from nonaneurysmal disease is less than 5.3 years, or if the elective surgical mortality rate quadruples from the reported 1.0% to 3.9%. Prompt elective surgery is more expensive than expectant management. Combining the effectiveness and cost data yields an incremental cost-effectiveness ratio for prompt elective surgery of $24,200 per QALY in the primary analysis. Sensitivity analysis shows the relative stability of this cost-effectiveness ratio, which is comparable to other common medical and surgical interventions. Prompt elective surgery is a cost-effective treatment for asymptomatic, unruptured, intracranial aneurysm provided: 1) the patient experiences a diminished quality of life from knowingly living with an asymptomatic, unruptured, intracranial aneurysm; 2) surgical morbidity and mortality remain similar to published rates; and 3) the patient has a life expectancy of 16.2 or more years.

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