Impact of Hospital Volume on the Economic Value of Computer Navigation for Total Knee Replacement

By James D. Slover, MD, MS, Anna N.A. Tosteson, ScD, Kevin J. Bozic, MD, MBA, Harry E. Rubash, MD, and Henrik Malchau, MD, PhD

Investigation performed at Massachusetts General Hospital, Boston, Massachusetts

Background: An aim of the use of computer navigation is to reduce rates of revisions of total knee replacements by improving the alignment achieved at the surgery. However, the decision to adopt this technology may be difficult for some centers, especially low-volume centers, where the cost of purchasing this equipment may be high. The purpose of this study was to examine the impact of hospital volume on the cost-effectiveness of this new technology in order to determine its feasibility and the level of evidence that should be sought prior to its adoption.

Methods: A Markov decision model was used to evaluate the impact of hospital volume on the cost-effectiveness of computer-assisted knee arthroplasty in a theoretical cohort of sixty-five-year-old patients with end-stage arthritis of the knee to coincide with the peak incidence of knee arthroplasty in the United States.

Results: Computer-assisted surgery becomes less cost-effective as the annual hospital volume decreases, as the cost of the navigation increases, and as the impact on revision rates decreases. Centers at which 250, 150, and twenty-five computer-navigated total knee arthroplasties are performed per year will require a reduction of the annual revision rate of 2%, 2.5%, and 13%, respectively, per year over a twenty-year period for computer navigation to be cost-effective.

Conclusions: Computer navigation is less likely to be a cost-effective investment in health-care improvement in centers with a low volume of joint replacements, where its benefit is most likely to be realized. However, it may be a cost-effective technology for centers with a higher volume of joint replacements, where the decrease in the rate of knee revision needed to make the investment cost-effective is modest, if improvements in revision rates with the use of this technology can be realized.

Level of Evidence: Economic and decision analysis, Level II. See Instructions to Authors for a complete description of levels of evidence.

The rate of primary and revision knee arthroplasty in the United States is increasing^{1,2}. Katz et al. reported that 11% of primary total knee arthroplasties were performed in hospitals at which less than twenty-five of these procedures were carried out per year and only 25% were performed in hospitals at which more than 200 procedures were done annually³. Several studies have demonstrated a relationship between increased complication rates and lower hospital volumes of total knee arthro-

plasty^{3,4}. The economic impact of revision procedures on hospital resource utilization is substantial⁵⁻⁷. Therefore, interventions aimed at reducing the complication and revision rates at centers with a low volume of joint replacements are important, as the number of primary and revision knee arthroplasties continues to grow.

Knee replacements may be associated with an increase in contact stresses and the need for revision if components are malaligned or malpositioned⁸⁻¹³. Sharkey et al. retrospectively

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Fig. 1

The Markov model used to model patients with end-stage arthritis of the knee. Each patient is treated with a total knee arthroplasty, either with computer-assisted surgery (CAS) or without computer-assisted surgery (TKA). If a patient survives the operation, that patient is considered to stay well until the time of death from other causes or the need for a revision. If a patient has a revision and survives, he or she is assumed to stay well with that revision until the time of death from other causes. The model continues until all patients reach the death health state.

reviewed the reasons for revision in 203 patients and found that 11.8% were due to component malalignment or malposition¹⁰. Several studies have suggested that the use of computer-assisted knee replacement improves component alignment and decreases the number of so-called outliers—i.e., cases of alignment outside of the generally preferred ranges¹⁴⁻¹⁹. The improved alignment achieved with computer navigation and the removal of outliers may decrease revision rates after total knee arthroplasty.

However, information is lacking regarding the impact of the improvements in alignment achieved with computer-assisted knee arthroplasty on short-term and long-term clinical outcomes or on implant survival. The decision to adopt this technology is particularly important for low-volume centers, where the incidence of complications may be higher and improvements in outcomes are most needed^{3,4,20,21}. The purpose of this study was to specifically examine the impact of hospital volume on the cost-effectiveness of this new technology in order to determine its feasibility and the level of evidence that should be sought prior to its adoption.

Materials and Methods

Patient Population

To model an elderly low-demand patient population, we evaluated a theoretical cohort of sixty-five-year-old patients with end-stage arthritis of the knee to coincide with the peak incidence of knee arthroplasty in the United States^{1,22}. All patients were assumed to have no contraindications to knee replacement.

Model Design

A Markov decision model²³ was used to determine the impact of a hospital's volume of total knee arthroplasties on the cost-effectiveness of computer-assisted surgery for the management of end-stage arthritis in this patient cohort (Fig. 1). The unit for cost was 2007 United States (U.S.) dollars, and the unit for effectiveness, or utility, was the quality-adjusted life-year (QALY)^{23,24}. The cycle length of the model was one year. All costs and utilities incurred after time zero were discounted at a rate of 3% per year to be consistent with current practices of cost-effectiveness analysis in medicine^{24,25}. The model was

TABLE I Model Parameters Used for Base Case

Parameter	Primary Total Knee Replacement without Computer Assistance	Primary Total Knee Replacement with Computer Assistance	Revision
Literature-derived parameters			
Probabilities			
Perioperative death	0.007	0.007	0.011
Utilities postop.	0.75	0.75	0.6
Utilities preop.	0.4	0.4	0.75
Assumed parameters			
Acute procedure toll	−0.1	−0.1	−0.2
Reimbursement parameters			
Common Procedural Terminology Code, Diagnosis-Related Group	27447, 544	27446, 544	27487, 545
Reimbursement	\$15,574	\$15,574	\$20,728
Navigation costs*			
Computer		\$100,000	
Software		\$40,000	
Maintenance contract		\$20,000 per year	
*Navigation costs represent the total cost of equipment, software, and maintenance. The cost per case was determined on the basis of the center volume, as described in the Materials and Methods section.			

constructed with use of decision analysis software (TreeAge Pro 2007; TreeAge Software, Williamstown, Massachusetts). The parameter values used in the decision model are shown in Table I and are individually described in further detail below and in the Appendix as indicated.

Model Parameters

Arthroplasty Survival Rates

The cohort used to determine the probability of revision was obtained from a 5% systematic Medicare sample from 1997 to 2004 for patients sixty-five years old and older, according to methods described in detail in a previous report²⁶. These data were used to set the annual probability of revision for patients in the model equal to the annual probability of revision in the Medicare population, for years 1 through 8. For years 9 through 13, we set the rate of revision at 0.8%, the rate of revision in year 8 in the Medicare cohort, and then set it at 1% per year for years 14 through 20 (see Appendix). The resulting implant survival rates are consistent with the long-term results reported in the Swedish National Hip Arthroplasty Register, validating these estimations used in the model (see Appendix)²⁷.

Mortality Rates

The age-specific probability of death from causes unrelated to knee replacement was made equal to the probability of death at each specific age and was obtained from the 2001 United States life tables²⁸. The probability of perioperative death for patients undergoing a total knee arthroplasty was estimated from a study of 124,986 primary total knee arthroplasties and 11,726 revision knee arthroplasties found in the 2000 Medicare database²². This study demonstrated a perioperative (ninety-day)

mortality rate of 0.7% for patients treated with primary knee replacement and 1.1% for those treated with revision knee replacement.

Health State Values

Utilities used in the model were based on scores for joint arthroplasties reported in the literature^{29,30}. The utility value after total knee replacement, with or without the assistance of computer navigation, was set at 0.75 QALY, which is consistent with the average utility values found for patient populations sixty-five years of age without arthritis (0.76 QALY)³¹ and the values found in the Swedish Registry after hip replacement (0.73 QALY)³². The preoperative utility value was set to be equal to the preoperative utility value for patients in the Swedish Registry before hip replacement (0.4 QALY)³². Although these values were obtained from analyses of patients with hip disease, they represent values obtained from analyses of over 13,000 patients with arthritis of a major lower-extremity joint and therefore are reasonable estimates of the utility values for patients with knee arthritis as well. The utility value after a knee revision was set at 0.6 QALY because studies have shown that the results of revision knee arthroplasty are generally poorer than those of a primary procedure³⁰.

Disutilities represent the negative preference that patients have for a particular health state or outcome, such as primary or revision knee arthroplasty. These negative utility values, or disutilities, account for the decreased mobility, increased pain, and potential complications that are incurred during the perioperative period. The disutility of having a total knee arthroplasty with or without navigation was set at −0.1 QALY, applied in year 1 after the surgery. A revision, which has been shown to be as-

of Cases per year and Annual Reduction in Revision Rate

Fig. 2

Results of the sensitivity analysis demonstrating the relationship between hospital volume and the reduction in the revision rate following primary total knee arthroplasty with computer-assisted surgery (CAS). The blue area demonstrates the profiles for which total knee arthroplasty with computer-assisted surgery is more cost-effective (the cost is less than \$50,000 per quality-adjusted life-year [QALY]). The green area demonstrates the profiles for which total knee arthroplasty without computer-assisted surgery is more cost-effective. The reduction in the revision rate is expressed as a percentage of the revision rate following total knee arthroplasty performed without navigation (TKA). For example, for computer navigation to be cost-effective at a center at which one hundred and sixty arthroplasties are performed per year, the reduction in revisions with the use of navigation would have to be just under 3%, or the revision rate would have to be just under 97% of the revision rate for total knee arthroplasties performed without navigation.

sociated with a much higher complication rate, a much longer recovery time, and a higher morbidity rate compared with primary total knee arthroplasty, was assessed a higher disutility value of -0.2 QALY.

Costs

Costs were measured in 2007 U.S. dollars. The costs of primary and revision total knee arthroplasties were estimated from reimbursement data from the Massachusetts General Hospital billing department. The average reimbursement for a primary total knee arthroplasty was based on the reimbursement for Diagnosis-Related Group (DRG) 544, and the average reimbursement for a revision total knee arthroplasty was based on DRG 545. Computer navigation costs were based on figures obtained from our hospital's purchasing department. The cost of the navigation computer (\$100,000), the computer software (\$40,000), and the service contract (\$20,000 per year) were obtained from the vendor. These costs were amortized to assign the appropriate amount to the first year, with the assumption of a five-year survival of the equipment and software. We allocated \$20,000 per year for five years for the

computer hardware, \$8000 per year for five years for the software, and \$20,000 per year for the service contract, yielding a net total cost of \$48,000 per year for five years. This yearly cost was then divided by the number of cases performed at the center per year to determine the cost per case of computer navigation (see Appendix).

Analysis

Cost-effectiveness was measured with use of the incremental cost-effectiveness ratio, which is the ratio of the difference in cost divided by the difference in effectiveness (expressed in QALYs in this model) between two different treatment strategies when they are ranked in order of increasing cost (see Appendix)^{23,24}. We considered computer-assisted-surgery profiles with incremental cost-effectiveness ratios of less than \$50,000 per QALY to be reasonably cost-effective, as that is consistent with previous practices of cost-effectiveness analysis²⁴. Two-way sensitivity analysis was used to examine the relationships among hospital volume, the annual cost of computer navigation, revision rates, and cost-effectiveness of computer-assisted surgery (see Appendix).

Sensitivity Analysis on Annual Cost of Navigation and Reduction in Revision Rate

Fig. 3-A

Figs. 3-A, 3-B, and 3-C Results of the sensitivity analyses demonstrating the relationship between the annual cost of computer navigation (CAS) and the reduction in the revision rates at centers at which joint replacements are performed. The blue area demonstrates the profiles for which total knee arthroplasty with computer-assisted surgery is more cost-effective (the cost is less than \$50,000 per quality-adjusted life-year [QALY]). The green area demonstrates the profiles for which total knee arthroplasty without computer-assisted surgery is more cost-effective. The reduction in the revision rate is expressed as a percentage of the revision rate following total knee arthroplasty performed without navigation (TKA). **Fig. 3-A** Results for centers at which 250 joint replacements are performed per year. For example, for computer navigation costing \$48,000 annually to be cost-effective, the center would need to have just under a 2% reduction in revisions with the use of navigation, or have a revision rate of just under 98% of the revision rate for total knee arthroplasties performed without navigation.

Sensitivity Analysis on Annual Cost of Navigation and Reduction in Revision Rate

Fig. 3-B

Results for centers at which 150 joint replacements are performed per year. For example, for computer navigation costing \$48,000 annually to be cost-effective, the center would need to have a 2.5% reduction in revisions with the use of navigation, or have a revision rate of 97.5% of the revision rate for total knee arthroplasties performed without navigation.

Sensitivity Analysis on Annual Cost of Navigation and Reduction in Revision Rate

Fig. 3-C

Results for centers at which twenty-five joint replacements are performed per year. For example, for computer navigation costing \$48,000 annually to be cost-effective, the center would need to have a 13% reduction in revisions with the use of navigation, or have a revision rate of 87% of the revision rate for total knee arthroplasties performed without navigation.

Results

The analysis demonstrated that computer-assisted surgery becomes less cost-effective as the annual hospital volume decreases and as the impact on revision rates decreases (Fig. 2). At a center at which 250 arthroplasties are performed per year, computer-assisted surgery will be cost-effective if the annual revision rate is reduced by 2% per year over a twenty-year period. At a center at which 150 arthroplasties are performed per year, computer-assisted surgery will be cost-effective if it results in a 2.5% reduction in the annual revision rate over a twenty-year period. At a center at which only twenty-five arthroplasties are performed per year, the annual reduction in the revision rate must be 13% for computer-assisted surgery to be cost-effective.

Sensitivity analysis was used to examine the impact of the cost of computer navigation on cost-effectiveness. The results are shown in Figures 3-A, 3-B, and 3-C. Figure 3-A demonstrates that, at centers at which 250 arthroplasties are performed per year, the annual reduction in the revision rate over twenty years that is necessary to make computer navigation cost-effective drops from 3% if the annual cost is \$80,000, to 1.8% if the annual cost is \$48,000, and to <1.0% if the annual cost is only \$20,000. Figure 3-B demonstrates that, at centers at which 150 arthroplasties are performed per year, the annual reduction in the revision rate over twenty years that is necessary to make computer navigation cost-effective drops from 4% if the annual cost is \$80,000, to 2.5% if the annual cost is \$48,000, and to 1.0% if the annual cost is only \$20,000. Figure 3-C demonstrates that, at centers at which twenty-five arthroplasties are performed per year, the annual reduction in the revision rate over twenty years that is necessary to make computer navigation cost-effective drops from 20% if the

annual cost is \$80,000, to 13% if the annual cost is \$48,000, and to 5.0% if the annual cost is only \$20,000.

Discussion

Several studies have demonstrated a relationship between increased complication rates and lower hospital volumes of total knee arthroplasty^{3,4}. This information could be used to advocate the concentration of knee arthroplasty procedures into regional, high-volume joint-replacement centers, which have historically achieved superior results³³. Alternatively, new technology, such as computer navigation, could be employed to improve the outcomes of surgeons and centers performing a low volume of joint replacements, allowing patients to continue to receive knee replacement surgery in these centers. Novak et al. recently used decision analysis techniques to examine the cost-effectiveness of computer-navigated knee surgery and concluded that computer navigation may be a cost-effective or even cost-saving technological advance in total knee replacement surgery³⁴. Computer navigation may enable these low-volume centers to improve the inferior outcomes by improving implant alignment, which in turn may improve long-term implant survival. However, we are aware of no study that has actually demonstrated a long-term decrease in revision rates in association with computer navigation. Despite the dearth of follow-up data, surgeons and patients have been encouraged by the concept that improved alignment achieved with computer navigation may improve patient outcomes by decreasing long-term revision rates and by marketing forces to pursue this new costly technology. However, these potential benefits must be carefully weighed against the cost of computer navigation, which may be a substantial obstacle, particularly in centers at which a low volume of joint replacements are performed.

The results of the present analysis demonstrate that hospital volume has a substantial impact on cost-effectiveness. With the assumption of a fixed life for the technology and equipment needed to perform computer-assisted surgery, the analysis demonstrated that the impact on annual revision rates must increase significantly as the number of cases per year at a given center decreases in order for the incremental cost-effectiveness ratio to remain below the threshold of \$50,000 per QALY (Fig. 2). Figures 3-A, 3-B, and 3-C demonstrate the impact of reduced navigation costs on the needed change in revision rates to make computer navigation cost-effective. They illustrate that, as the annual cost of navigation decreases from \$80,000 per year to \$20,000 per year, the reduction in the annual revision rate over a twenty-year period that is needed for computer navigation to be cost-effective decreases from 3% to <1% at centers at which 250 arthroplasties are performed per year and from 20% to 5% at centers at which only twenty-five arthroplasties are performed per year. These are substantial reductions, particularly for low-volume centers, and evidence of substantial reductions in revision rates or substantial decreases in the cost of computer navigation will be needed to make this technology cost-effective. To place this in context, a recent study showed the annual revision total knee arthroplasty burden in the United States to be 8.2%, with a revision rate of 5.4 procedures per 100,000 persons per decade from 1990 to 2002. To reduce this by 20% by using computer navigation, the revision burden would need to be reduced to 6.5%³⁵. Another recent analysis of a cohort of U.S. Medicare patients showed the eight-year survival rate of total knee prostheses to be 96%²⁶. The survival rate would need to be increased to up to 96.5% in low-volume centers for computer navigation to be cost-effective. This analysis suggests that the investment in this technology may not be cost-effective for low-volume centers because the annual reduction in revision rates necessary to make it cost-effective may be too high. However, considerable reductions may be possible in low-volume centers, where the revision rate due to malaligned or malrotated components may be higher than average, and therefore the impact of computer navigation on revision rates merits study in these low-volume centers.

These findings pose an important dilemma for these low-volume centers because they suggest that the monetary investment in a navigation system may be more prudently spent on improvement in other areas, where the cost per QALY gained would be lower, allowing for a higher total QALY gain for the resource investment. It is easy to declare that an intervention is not cost-effective because its effect on the population is small. However, to the one individual patient who may have been helped by the intervention, the complication is of course large. However, as a profession we can no longer spend money as we please. Therefore, cost-effectiveness considerations on a population level are now important so that we can achieve maximum improvements for dollars spent. We hope, however, that cost-effectiveness will never be the only consideration.

Alternative options other than purchase, such as lease or rental agreements or cost-sharing strategies, should be

considered in order to reduce the cost per case for employing this technology in these low-volume centers and improve cost-effectiveness. In addition, when possible, low-volume surgeons may consider combining resources for the purchase of computer navigation to be used at a single center in order to reduce the cost of the technology and improve cost-effectiveness.

A limitation of this study is the estimation of other transition probabilities within the model. Estimates of mortality rates associated with total knee arthroplasty were obtained from large cohort studies of patients treated with arthroplasty procedures in the past²². The rate estimated from the results of these studies may be different from the risks assumed by a patient treated with an arthroplasty today. In addition, these and other complication rates, such as infection rates, may differ between high and low-volume centers. Furthermore, the model does not account for patients with loosening of the knee replacement that does not lead to revision. These patients may demonstrate poor health utility values, which would not be reflected in the model, and the number of patients in this state may differ between the two groups. An additional limitation is the assumption that no repeat revision procedures are necessary. The cost of each primary and revision operation was estimated on the basis of our hospital's average reimbursement for these procedures. However, actual local reimbursements may differ from this amount. In addition, the use of reimbursement data represents the costs from a payer point of view. The costs to payers who reimburse for these procedures may differ substantially from the costs to care providers, who provide a diverse array of primary and ancillary services in the care of these patients. Indirect costs to patients and providers, such as lost wages or the cost of increased operating room time, were also not included. Furthermore, the costs of the computer navigation equipment, software, and maintenance were determined from information obtained from the purchasing department at our institution, and these values may differ from the costs to other joint centers. Therefore, the cost of these procedures and the cost of computer navigation may have been overestimated or underestimated in our model.

In conclusion, this analysis demonstrates that computer-assisted knee arthroplasty may be a cost-effective technology at centers at which a higher volume of joint replacements are performed, where the decrease in the rate of knee revision needed to make the investment cost-effective is modest. However, it is less likely to be a cost-effective investment in health-care improvement at centers at which a low volume of joint replacements are performed unless the annual reduction in the revision rate of 20% that is needed to make it cost-effective can be achieved. Long-term studies are necessary to determine the impact of computer-assisted surgery on knee arthroplasty revision rates before its widespread adoption. Finally, this analysis demonstrates that hospital volume can have a substantial impact on the cost-effectiveness of new technology in surgery, especially when large capital investments, such as for the purchase of computers or software, are necessary for its im-

plementation. This fact must be carefully considered when the decision to adopt new technology in a surgical care setting is undertaken.

Appendix

Additional text describing in detail the methods used to construct the Markov model and a table showing the total knee implant survival rates used in the model are available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on “Supplementary Material”) and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM). ■

James D. Slover, MD, MS
Department of Orthopaedic Surgery,
NYU Hospital for Joint Diseases, 301 East 17th Street,
Suite 1616, New York, NY 10010.
E-mail address: james.slover@nyumc.org

Anna N.A. Tosteson, ScD
Multidisciplinary Clinical Research Center in Musculoskeletal Diseases,
HB7505, Dartmouth Medical School, One Medical Center Drive,
Lebanon, NH 03756

Kevin J. Bozic, MD, MBA
Department of Orthopaedic Surgery,
University of California at San Francisco,
500 Parnassus Avenue, MU 320W,
San Francisco, CA 94143

Harry E. Rubash, MD
Department of Orthopaedic Surgery,
Massachusetts General Hospital,
55 Fruit Street, Yawkey Suite 3700,
Boston, MA 02114

Henrik Malchau, MD, PhD
Department of Orthopaedic Surgery,
Massachusetts General Hospital,
55 Fruit Street, GR1126,
Boston, MA 02114

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