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The Cost-Effectiveness of Surgical Treatment of Medial Unicompartmental Knee Osteoarthritis in Younger Patients

A Computer Model-Based Evaluation

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Background: Surgical options for the management of medial compartment osteoarthritis of the varus knee include high tibial osteotomy, unicompartmental knee arthroplasty, and total knee arthroplasty. We sought to determine the cost-effectiveness of high tibial osteotomy and unicompartmental knee arthroplasty as alternatives to total knee arthroplasty for patients fifty to sixty years of age.

Methods: We built a probabilistic state-transition computer model with health states defined by pain, postoperative complications, and subsequent surgical procedures. We estimated transition probabilities from published literature. Costs were determined from Medicare reimbursement schedules. Health outcomes were measured in quality-adjusted life-years (QALYs). We conducted analyses over patients' lifetimes from the societal perspective, with health and cost outcomes discounted by 3% annually. We used probabilistic sensitivity analyses to account for uncertainty in data inputs.

Results: The estimated discounted QALYs were 14.62, 14.63, and 14.64 for high tibial osteotomy, unicompartmental knee arthroplasty, and total knee arthroplasty, respectively. Discounted total direct medical costs were \$20,436 for high tibial osteotomy, \$24,637 for unicompartmental knee arthroplasty, and \$24,761 for total knee arthroplasty (in 2012 U.S. dollars). The incremental cost-effectiveness ratio (ICER) was \$231,900 per QALY for total knee arthroplasty and \$420,100 per QALY for unicompartmental knee arthroplasty. Probabilistic sensitivity analyses showed that, at a willingness-to-pay (WTP) threshold of \$50,000 per QALY, high tibial osteotomy was cost-effective 57% of the time; total knee arthroplasty, 24%; and unicompartmental knee arthroplasty, 19%. At a WTP threshold of \$100,000 per QALY, high tibial osteotomy was cost-effective 43% of time; total knee arthroplasty, 31%; and unicompartmental knee arthroplasty, 26%.

Conclusions: In fifty to sixty-year-old patients with medial unicompartmental knee osteoarthritis, high tibial osteotomy is an attractive option compared with unicompartmental knee arthroplasty and total knee arthroplasty. This finding supports greater utilization of high tibial osteotomy for these patients. The cost-effectiveness of high tibial osteotomy and of unicompartmental knee arthroplasty depend on rates of conversion to total knee arthroplasty and the clinical outcomes of the conversions.

Level of Evidence: Economic Level II. See Instructions for Authors for a complete description of levels of evidence.

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There is no consensus as to the optimal surgical treatment for patients in their fifties with end-stage medial unicompartmental osteoarthritis, varus deformity, and persistent symptoms despite nonoperative therapy. Surgical options include valgus-producing high tibial osteotomy (HTO), unicompartmental knee arthroplasty (UKA), and total knee arthroplasty (TKA). Each option has advantages and disadvantages¹.

Periarticular HTO is an accepted treatment in young, active patients with medial compartment osteoarthritis. It provides reliable pain relief by altering the mechanical axis of the lower limb to unload the arthritic compartment. Compared with knee arthroplasty, HTO may provide more natural kinematic function because the joint is not opened and structures about the knee are retained². However, long-term HTO survival has ranged from 30% to 90%³, and the function of a TKA performed following an HTO is not well established⁴⁻⁶.

UKA was traditionally indicated for patients older than sixty years of age⁷. With improved implant design and surgical technique, UKA increasingly has been used in younger patients⁸. Compared with TKA, a well-functioning UKA may result in improved range of motion, better gait pattern, shorter recovery

period, and lower rate of deep venous thrombosis⁹. However, implant survivorship has varied, from 70% to 96.5% at five to ten years of follow-up, and higher rates of revision relative to TKA have been observed in multiple joint registries¹⁰⁻¹⁸.

In recent decades, younger patients with end-stage osteoarthritis increasingly have been offered TKA, although these patients may expose the implant to greater mechanical stress¹⁹. While survival rates of TKA may exceed those of UKA in younger patients¹⁰, revision TKA may be more technically complex and expensive than primary TKA or revision UKA²⁰.

Two recent studies compared the cost-effectiveness of UKA and TKA in older patients, finding UKA to be cost-effective if survivorship exceeded twelve years²¹ or failure rates were <4% annually²². Other recent studies were limited by excluding quality-of-life analysis²³ or by use of only short-term data²⁴. Brown et al.²⁵ compared the cost-effectiveness of HTO, UKA, and TKA in forty-year-old patients, finding that UKA produced the highest health benefit at an ICER (incremental cost-effectiveness ratio) of \$1048 per QALY (quality-adjusted life-year) (in 2008 U.S. dollars). However, subsequent studies suggest that the failure rate of UKA used in this model was too

TABLE I Key Base Case Input Parameters*

	HTO	UKA	Primary TKA	Aseptic Revision TKA	Septic Revision TKA
Transition probabilities					
Early implant failure†	3.36% ^{58,59,99,106}	2.63% ^{11,13,15,16,18,26}	0.57% ^{10,15,16,62}	3.53% ^{20,53}	3.53% ^{20,52}
Late implant failure†	2.32% ^{3,10,40}	2.32% ^{11,13,15,16,18,26}	1.21% ^{6,15,17,23,26,29,34,39,60,62}	3.53% ^{20,53}	3.53% ^{20,52}
Revision failure	1.6% ⁶	1.6% ^{6,20,53,107}	3.53% ^{20,53}	3.53% ^{20,52}	3.53% ^{20,53}
Quality of life (QALYs)					
Optimal implant§	0.835 ^{3,40,108}	0.835 ^{17,24,27,34,69,73}	0.835 ^{21,22,25,61,68,74,109}	0.772 ^{21,22,25,64,67,109}	0.756 ^{22,110}
Optimal revision#	0.804 ^{4,6,85,86,88,90,111}	0.804 ^{6,13,75,78}	0.772 ^{21,22,25,63,66,108}	0.772 ^{21,22,25,64,67,109}	0.756 ^{22,109}
Aseptic failure	0.69 ^{21,22,25,62,65,68,74}	0.69 ^{21,22,25,62,65,68,74}	0.69 ^{21,22,25,62,65,68,74}	0.69 ^{21,22,25,62,65,68,74}	0.69 ^{21,22,25,62,65,68,74}
Septic failure	0.5 ^{21,22,25}	0.5 ^{21,22,25}	0.5 ^{21,22,25}	0.5 ^{21,22,25}	0.5 ^{21,22,25}
Costs (2012 USD)					
Preop. work-up**	\$236 ^{112,114}	\$236 ^{112,114}	\$236 ^{112,114}	\$236 ^{112,114}	\$641 ^{112,114}
Anesthesia fee	\$323 ¹¹⁵	\$323 ¹¹⁵	\$387 ¹¹⁵	\$482 ¹¹⁵	\$805 ¹¹⁵
Surgeon fee	\$962 ¹¹²	\$1109 ¹¹²	\$1544 ¹¹²	\$1768 ¹¹²	\$3302 ¹¹²
Surgery and acute care	\$6135 ⁹²	\$9831 ⁹²	\$9831 ⁹²	\$12,784 ⁹²	\$17,425 ⁹²
Rehabilitation or home therapy††	\$2099 ^{92,116}	\$1618 ^{92,116}	\$3383 ^{92,116}	\$5376 ^{92,116}	\$10,593 ^{92,116}
Additional postop. costs‡‡	\$252 ^{112,113,116}	\$252 ^{112,113,116}	\$252 ^{112,113,116}	\$252 ^{112,113,116}	\$364 ^{112,113,116}
Annual postop. evaluations§§	—	\$93 ^{112,113,117}	\$93 ^{86,112,118}	\$93 ^{86,112,118}	\$93 ^{86,112,118}
Additional costs##	—	—	—	—	\$4635 ^{112,114}

*HTO = high tibial osteotomy, UKA = unicompartmental knee arthroplasty, and TKA = total knee arthroplasty. †The probability of failure of the implant within one year of the procedure. ‡The annual probability of implant failure after one year postoperatively. §The annual QALYs gained from an optimal implant. #The annual QALYs gained from an optimal revision of the implant. **Includes physician visit, preoperative imaging, and preoperative laboratory tests. ††Average expense of postoperative care based on the patient's expected disposition to a rehabilitation facility or home, with or without home health care or outpatient physical therapy. ‡‡Additional postoperative medications and additional physician visits and imaging outside of the ninety-day global reimbursement window. §§Average annualized costs of physician visits and imaging after the first postoperative year. ##Additional expenses associated with a septic knee prosthetic revision, including infectious disease consultation and follow-up visits, central venous access, intravenous antibiotics, laboratory monitoring while on intravenous antibiotics, and knee aspirations.

low^{8,10-15,17,18,23,26-39} and that the failure rate of HTO was too high^{3,6,40}.

Our goal was to examine the cost-effectiveness of HTO and UKA as alternatives to TKA for the treatment of medial compartment osteoarthritis with varus deformity in patients fifty to sixty years old—a decade during which indications for these procedures overlap.

Materials and Methods

Analytic Overview

We built a state-transition computer model of alternative surgical treatments for patients who failed conservative therapy for medial unicompartmental osteoarthritis with varus deformity. The model was created using TreeAge Pro software (TreeAge Software, Williamstown, Massachusetts)⁴¹. Outcomes included QALYs, costs, and ICERs. A QALY is a measurement of quality of life defined on a 0 to 1 scale; a year of perfect health is worth 1 QALY, and a year of less than perfect health is worth <1 QALY⁴². The value of a QALY reflects patient morbidity and lost productivity⁴³. Both QALYs and costs were discounted by 3% annually. ICERs were calculated as the difference in costs divided by the difference in QALYs between two treatments. ICERs quantify the additional cost-per-QALY gained in switching from one medical intervention to another⁴⁴, thereby allowing comparison of the value provided by different health interventions. We evaluated three surgical strategies: HTO, UKA, and TKA. Our analysis conformed to the guidelines of the U.S. Panel on Cost-Effectiveness in Health and Medicine⁴⁵.

Willingness-to-pay (WTP) per QALY is the limit at which society is no longer willing to spend resources to gain additional QALYs⁴⁵. We considered three commonly used WTP thresholds: \$50,000 per QALY, \$100,000 per QALY, and \$150,000 per QALY⁴⁶. A treatment was considered cost-effective if its ICER was below the WTP threshold and was “dominated” if it was less effective but more costly than an alternative. If a treatment’s ICER was greater than that of more effective alternatives, we refer to it as having “extended dominance.”⁴⁷

Additionally, we performed value-of-information analyses. These analyses determine the benefit from obtaining additional information to eliminate uncertainty and better inform a decision. We estimated the expected value of partial perfect information (EVPPPI) by hypothetically eliminating the uncertainty in several model parameters. This allowed us to identify targets for future research⁴⁸.

We estimated the benefit to society by multiplying the benefit per patient by the number of patients in the fifty-to-sixty age range who would face treatment decisions annually⁴⁹⁻⁵².

Model Structure

Figure 1 illustrates the Markov model structure. Patients entered the simulation at the time of surgery. The model independently accounted for perioperative medical and surgical complications. Medical complications included myocardial infarction, deep venous thrombosis, pulmonary embolism, and death, and surgical complications included aseptic failure, nonunion, or deep infection. Surgical results were stratified as “optimal” or “suboptimal,” with those in the “optimal” state having greater quality of life. Patients in a “suboptimal” state were those with pain, aseptic component loosening, or disease progression. Each year, patients could transition from “optimal” to “suboptimal” or remain in the same health state as the previous year. Patients in a “suboptimal” state were at risk for a revision procedure, which was assumed to be a TKA for those whose index procedure was HTO or UKA⁵³. Patients with a knee implant failure due to sepsis undergo a two-stage revision procedure⁵⁴. After revision, patients were similarly stratified to an “optimal” or “suboptimal” post-revision state, which was associated with lower quality of life than the corresponding primary procedure. Patients within a “suboptimal” post-revision state were at risk for repeat revision surgery. Patient age at the time of the initial procedure ranged from fifty to sixty years, with an average of fifty-five years. We conducted the analysis over patients’ lifetimes. Table I summarizes input parameters, which were stratified by transition probabilities, quality of life, and costs.

Transition Probabilities

The probability of perioperative medical complications was obtained from literature that investigated complications among age-stratified TKA patients⁵⁵ and was assumed to be similar for UKA, HTO, and revision procedures^{40,56,57}. After the initial procedure, patients had a 1.1% chance of medical complications. For subsequent procedures, patients experienced a higher probability of medical complications on the basis of their age. Annual other-cause mortality was determined from United States Life Tables⁴⁹.

The probability of HTO failure after one year was assumed to be the same as that of UKA failure on the basis of a Swedish registry study and two recent meta-analyses^{3,10,40}. We estimated a 3.36% rate of deep infection or nonunion

Fig. 1
The structure of the Markov model for high tibial osteotomy (HTO), unicompartmental knee arthroplasty (UKA), and total knee arthroplasty (TKA). Diamonds represent transition states during which a surgical intervention occurs. Ovals represent transition states during which no surgical intervention occurs. Straight arrows indicate a transition to a different transition state, and curved arrows indicate staying in the same transition state. Two transition states are not depicted: permanently living with a suboptimal prosthesis and the absorbing death state.

TABLE II Cost-Effectiveness of High Tibial Osteotomy (HTO), Unicompartmental Knee Arthroplasty (UKA), and Total Knee Arthroplasty (TKA) in the Base Case Analysis*

Intervention	Cost	QALY	ICER (cost per QALY)	Conversion to TKA within Ten Years (Std. Dev.)	Conversion to TKA within Lifetime (Std. Dev.)	Revision TKA within Ten Years (Std. Dev.)	Revision TKA within Lifetime (Std. Dev.)
HTO	\$20,436	14.62	—	16% (1.2%)	40% (1.5%)	0.9% (0.4%)	10% (0.9%)
UKA	\$24,637	14.63	Extended dominance†	18% (1.2%)	42% (1.5%)	1.4% (0.4%)	11% (1.0%)
TKA	\$24,761	14.64	\$231,900	—	—	10.7% (1.0%)	37% (1.4%)

*QALY = quality-adjusted life-year, and ICER = incremental cost-effectiveness ratio. †In extended dominance, an intervention has an ICER that is greater than that of a more effective alternative; ICER = \$420,100.

within one year following HTO from recent reviews of HTO complications^{58,59}. The probability of UKA failure was determined from a literature search of studies from 2004 to 2013. Of twenty-seven studies identified, nine studies analyzed revision rates in a cohort of UKA patients younger than sixty-one years old^{11-18,26}. From these studies, we derived a UKA implant failure rate of 2.63% during the first postoperative year and 2.32% annually thereafter.

We estimated the probability of TKA failure at 0.57% within the first year and 1.21% in subsequent years by summarizing published literature regarding TKA failure rates for the appropriate patient age range^{6,10,15-17,23,29,34,39,60}. We derived a 3.53% annual failure rate of a revision TKA requiring a repeat surgery as a weighted average of results reported in registry data^{20,53}.

All patients with a prosthetic failure due to sepsis were treated with a two-stage revision⁵⁴. We assumed that 100% of patients who had an aseptic prosthetic failure within the first year would undergo revision surgery, whereas patients with an aseptic failure in subsequent years were assumed to undergo revision on the basis of their age at the time of failure, with fewer elderly patients electing to undergo a revision.

Quality of Life

Median reported QALYs for an optimal TKA among recent studies was 0.835^{21,22,25,61-68}. Quality of life for an optimal primary HTO, UKA, and TKA was assumed to be similar on the basis of nine studies that compared UKA with TKA within the last decade and found similar clinical scores using a variety of validated instruments^{11,17,24,27,34,69-73} as well as on the basis of two recent meta-analyses comparing HTO and UKA^{3,40}. Median reported QALYs after an optimal revision TKA was 0.772^{21,22,25,62,64,65,68,74}. Data on the performance of HTO^{5-7,36,65-70} or UKA^{6,13,75-78} converted to TKA have been limited. Some studies have found that conversions of HTO and UKA to TKA have results similar to primary TKA, while other studies have found worse outcome scores relative to primary TKA. Therefore, we estimated the quality of life for conversion of both HTO and UKA to TKA to be midway between that of primary and revision TKA, or 0.804 QALYs. On the basis of published literature, we incorporated a 40% loss of QALYs during a twelve-week recovery after a TKA, HTO, or revision procedure, and a 30% loss of QALYs during recovery from a UKA^{21,25,67,79}.

Costs

We included costs associated with primary HTO, UKA, and TKA procedures as well as conversion of HTO and UKA to TKA, TKA revision due to aseptic failure, two-stage revision due to septic failure, debridement for deep infection following an HTO, and revision due to nonunion following HTO. For each procedure, we used average Medicare reimbursement rates to estimate costs of physician visits, preoperative imaging, preoperative laboratory tests, anesthesia fees, surgeon fees, surgery-related technical needs, acute inpatient recovery, major medical complications, postoperative rehabilitation, and postoperative evaluations. Costs were varied by 30% above and below the base value in sensitivity analyses. All costs were expressed in 2012 U.S. dollars using the medical component of the Consumer Price

Index⁸⁰. We estimated average total first-year costs of an uncomplicated HTO, UKA, and TKA at \$10,006, \$13,369, and \$15,634, respectively (see Appendix).

Sensitivity Analyses

We conducted sensitivity analyses to determine how data uncertainty affects the result. We utilized one-way and two-way deterministic sensitivity analyses to evaluate how the cost-effectiveness of treatment strategies changes as a result of variations in specific model parameters. Additionally, we conducted a probabilistic sensitivity analysis to determine the effect of joint uncertainty in multiple parameters by repeating a cost-effectiveness analysis 10,000 times. Each time, the model drew parameters from prespecified distributions that took uncertainty around point estimates into consideration. We used beta distributions for implant failure rates because the beta distribution is ideal for binomial data in which the number of failures in a given sample size is known⁸¹. We constructed a cost-effectiveness acceptability curve, which demonstrates the probability that an intervention is cost-effective over a range of WTP thresholds⁸² (see Appendix).

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Results

Base Case

Table II presents the results of the base case analysis. Patients undergoing HTO and UKA had an estimated 16% and 18% chance, respectively, of undergoing conversion to TKA within ten years, and a 40% and 42% chance, respectively, of having a conversion to TKA within their lifetime. Patients undergoing HTO and UKA had a 10% and 11% chance, respectively, of requiring both conversion to TKA and eventual revision TKA within their lifetime. In contrast, primary TKA patients had a 37% chance of undergoing a revision TKA in their lifetime.

We estimated QALYs of 14.62, 14.63, and 14.64 for HTO, UKA, and TKA, respectively. Lifetime direct medical costs were \$20,436 for HTO, \$24,637 for UKA, and \$24,761 for TKA. TKA demonstrated an ICER of \$231,900 per QALY gained, which was higher than our highest WTP threshold of \$150,000. UKA was less effective and less costly than TKA but had an even greater ICER: \$420,100 per QALY. It was therefore determined to have shown extended dominance.

We estimated that HTO could save approximately \$4263, on average, compared with UKA or TKA, when considering

Fig. 2

Two-way sensitivity analyses of the rates of conversion to total knee arthroplasty (TKA) for unicompartmental knee arthroplasty (UKA) versus high tibial osteotomy (HTO) (**left panel**) and the utility of conversion for UKA versus HTO (**right panel**). Cost-effectiveness was compared when the annual rates of conversion and annual utility derived from conversion were allowed to vary. The willingness-to-pay (WTP) threshold of \$100,000 per quality-adjusted life-year (QALY) is depicted by a solid line, and the WTP threshold of \$50,000 per QALY is depicted by the dashed line. The base case is indicated by the white square.

Fig. 3

Cost-effectiveness scatter plot of a Monte Carlo model of 10,000 theoretical patients, fifty to sixty years of age, undergoing each surgical strategy. Each outcome is represented by a dot colored to correspond with the primary surgery. The mean values for high tibial osteotomy (HTO), total knee arthroplasty (TKA), and unicompartmental knee arthroplasty (UKA) are represented by the large diamond, square, and triangle, respectively.

Fig. 4

Cost-effectiveness acceptability curve. This figure demonstrates the probability of each surgical option being the cost-effective strategy at a given willingness-to-pay threshold, utilizing a Monte Carlo simulation of 10,000 patients. HTO = high tibial osteotomy, TKA = total knee arthroplasty, and UKA = unicompartmental knee arthroplasty.

complications, conversions, and revision throughout the patient's lifetime.

Sensitivity Analyses

Conversion to TKA

Cost-effectiveness results were sensitive to annual conversion rates of both HTO and UKA to TKA (Fig. 2, left panel). At the WTP threshold of \$100,000 per QALY, if the HTO annual conversion rate increased to 2.6% from a baseline value of 2.3% annually, then TKA became the cost-effective strategy. Similarly, if the UKA annual conversion rate fell to <2.0%, then UKA became the cost-effective strategy. However, at the lower WTP threshold of \$50,000 per QALY, the findings were more robust: TKA became the cost-effective strategy only if the HTO annual conversion rate increased to 2.9%, from a baseline value of 2.3% annually.

Quality of Life

The results were also sensitive to quality of life for the conversion of both HTO and UKA to TKA (Fig. 2, right panel). If the QALY associated with a satisfactory conversion of HTO to TKA was 14% less than the baseline value of 0.804, TKA became a cost-

effective strategy. If the QALY from a satisfactory conversion of UKA to TKA was 19% greater than the baseline of 0.804, then UKA became a cost-effective strategy. Similarly, the findings were more robust at a lower WTP of \$50,000 per QALY: TKA became the cost-effective strategy only if the QALY from a satisfactory conversion of HTO to TKA was 36% lower than the baseline value of 0.804.

Several factors had no bearing on cost-effectiveness, including deep infection and nonunion rates of HTO and a plausible range of rehabilitation costs, acute recovery costs, and physician fees for HTO, UKA, and TKA.

Probabilistic Sensitivity Analysis

Figure 3 shows a cost-effectiveness scatter plot of 10,000 iterations of cost-effectiveness analyses. This figure demonstrates possible outcomes for costs and effectiveness for each procedure when joint uncertainty regarding multiple parameters was considered. The cost-effectiveness acceptability curve (Fig. 4) shows the frequency at which each strategy was found to be cost-effective over 10,000 iterations. At the WTP threshold of \$50,000 per QALY, HTO was cost-effective in 57% of the simulations;

TABLE III Expected Value of Partial Perfect Information*

Distribution	Per Patient NMB at WTP \$50,000	U.S. Annual Estimated Societal Benefit at WTP \$50,000†	Per Patient NMB at WTP \$100,000	U.S. Annual Estimated Societal Benefit at WTP \$100,000†
QALY from optimal UKA	\$201	\$6,705,088	\$2037	\$68,115,741
QALY factor for revisions‡	\$72	\$2,405,875	\$1561	\$52,196,715
QALY from optimal HTO	\$44	\$1,458,369	\$920	\$30,763,166
HTO early and late failure rates	\$23	\$772,648	\$201	\$6,718,796
UKA early and late failure rates	\$0	\$0	\$53	\$1,777,325
UKA converted to TKA failure rate	\$0	\$0	\$20	\$661,983
HTO converted to TKA failure rate	\$0	\$0	\$12	\$400,533

*UKA = unicompartmental knee arthroplasty, HTO = high tibial osteotomy, TKA = total knee arthroplasty, NMB = net monetary benefit, and WTP = willingness-to-pay. †The annual estimated societal benefit of the elimination of uncertainty surrounding key parameters. This is based on an estimated 33,000 patients annually with surgically treated unicompartmental osteoarthritis in the fifty to sixty-year-old age range⁵⁰⁻⁵². ‡This factor represents how much utility is derived from a revision procedure relative to a primary procedure.

TKA, in 24%; and UKA, in 19%. At the WTP threshold of \$100,000 per QALY, HTO was cost-effective in 43% of the simulations; TKA, in 31%; and UKA, in 26%.

EVPPPI

EVPPPI analysis (Table III) indicated that the greatest benefit was derived from eliminating uncertainty surrounding the quality of life experienced following optimal UKA and HTO relative to TKA as well as the quality of life derived from UKA and HTO conversions to TKA. Less benefit was derived from further reducing uncertainty regarding failure rates of UKA and HTO to TKA.

Discussion

We examined the cost-effectiveness of HTO, UKA, and TKA in younger patients with advanced medial unicompartmental knee osteoarthritis. Within WTP thresholds of \$50,000 per QALY to \$150,000 per QALY, HTO demonstrated the highest likelihood of being the most cost-effective treatment. Our results support greater utilization of HTO in younger persons with medial unicompartmental knee osteoarthritis. However, uncertainty surrounding key parameters, including quality-of-life improvements from conversion of HTO and UKA to TKA, prevents the dismissal of UKA and TKA as reasonable treatment options on cost-effectiveness grounds.

HTO and UKA are often used to “buy time” for younger patients until TKA is ultimately undertaken. Our model predicts that both HTO and UKA effectively delay the need for TKA, with rates of conversion within ten years of 16% and 18%, respectively, which is consistent with published data⁸³. Furthermore, both procedures delay the need for revision TKA, which may have the poorest outcomes^{20,53}. In contrast, our estimated lifetime TKA revision rate for primary TKA was 37%, which is consistent with reported survivorship in younger patients⁸⁴.

The clinical performance of HTO converted to TKA is not well established, with some studies suggesting worse outcomes relative to primary TKA and others suggesting similar out-

comes^{4-6,28,85-90}. Likewise, data on UKA conversions are inconsistent^{76,91,92}, although several authors have demonstrated that UKA converted to TKA compares unfavorably with primary TKA, with increased technical complexity^{77,78,93-95}, poorer function^{6,13,75,77,78,96}, and higher revision rates^{6,53}. Two studies that directly compared HTO and UKA conversions to TKA found better results with HTO conversions^{6,97}. Our study found that HTO is cost-effective even if the quality of life from a conversion to TKA is between that of primary TKA and revision TKA. However, a UKA converted to a TKA needed to approach the quality of life of primary TKA for UKA to be cost-effective.

The results of our analysis, which focused on younger patients, add to existing literature on cost-effectiveness of UKA and TKA in older patients. Soohoo et al.²¹ found that UKA had similar lifetime costs and effectiveness as TKA in sixty-five-year-olds, as long as UKA survival was within three to four years of TKA survival. Slover et al.²² found that UKA was cost-effective in seventy-eight-year-olds, as long as annual revision rates were <4%. Our study found that an HTO conversion rate of <2.6% annually and a UKA conversion rate of <2.0% annually are necessary for these procedures to be cost-effective options for younger patients.

The results of probabilistic sensitivity analysis suggested uncertainty regarding the cost-effectiveness of HTO. At the WTP threshold of \$50,000 per QALY, the probability that HTO is cost-effective did not exceed 57%. Although HTO had the highest probability of being the cost-effective strategy throughout the policy-relevant WTP range of \$50,000 per QALY to \$150,000 per QALY, the current state of the data precludes us from rejecting UKA and TKA on cost-effectiveness grounds. Although HTO leads to lower costs, surgeon experience and patient preferences are key factors that we could not model. From an implementation perspective, HTO may be more technically difficult than UKA or TKA, and its success may be driven by surgeon volume. Such factors may substantially influence outcomes.

Our study had several limitations. In the absence of data, we assumed an age-based rate of revision surgery for aseptic

prosthetic failures. We also assumed similar age-adjusted medical complication rates for primary and revision procedures. However, sensitivity analyses demonstrated that the outcome of our study was not affected by these assumptions. Additionally, where data from multiple sources were available, we derived pooled results from existing studies weighted by study sample sizes. In recognition of inconsistent results across studies, we performed deterministic and probabilistic sensitivity analyses to examine the effects of these uncertainties on our conclusions.

As previous authors have noted^{21,98}, a wide range of estimates for postoperative QALYs are reported throughout the literature, even for TKA. In the absence of studies designed to directly measure the utility of HTO, UKA, and TKA, as well as subsequent revisions, we used the median of reported values for the QALYs derived from TKA. We assumed the quality of life derived from HTO and UKA was similar on the basis of studies that measured relative outcomes with knee-specific outcome instruments. Furthermore, we estimated that the QALYs derived from HTO or UKA converted to TKA were midway between that of revision TKA and primary TKA on the basis of a small number of reports comparing these procedures.

Our study finds that in fifty to sixty-year-old patients with medial unicompartmental knee osteoarthritis, HTO is, from a cost-effectiveness perspective, an attractive treatment option compared with UKA and TKA. Among the three strategies considered, HTO had the highest probability of being cost-effective, and UKA had the lowest likelihood of being cost-effective; this conclusion is sensitive to annual conversion rates to TKA. Our findings support greater utilization of HTO in patients of this age range with medial knee osteoarthritis, if annual conversion rates of HTO are <2.6% and UKA conversion rates are >2.0%. However, based on uncertainty in key efficacy parameters in the current literature, no strategy could be uniformly supported or rejected on cost-effectiveness grounds. We recommend that additional research be directed at clarifying the utility derived from HTO and UKA when converted to TKA. Randomized controlled trials comparing long-term outcomes of TKA, HTO, and UKA, including index TKA revision and conversion of HTO and UKA to TKA and subsequent TKA revision, would further inform medical decision-making for younger patients with medial unicompartmental osteoarthritis.

Appendix

The methods used for deriving costs for each surgery and the distributions used for probabilistic sensitivity analysis are described below.

Costs

Preoperative Costs

Preoperative costs included the initial physician visit, preoperative imaging, and preoperative laboratory tests, and were derived from the Centers for Medicare & Medicaid Services (CMS) 2012 Physician Fee Schedule¹¹², Hospital Outpatient Prospective Payment System rules¹¹³, and the 2012 Clinical Laboratory Fee Schedule¹¹⁴.

Procedure Costs

Anesthesia professional fees were determined from the CMS Anesthesia Fee Schedule for 2012¹¹⁵. Surgeon fees were also de-

termined from the 2012 Physician Fee Schedule. Surgery-related technical needs and acute inpatient recovery costs were determined using the appropriate DRG (diagnosis-related group).

Post-Acute Recovery Costs

Costs associated with postoperative rehabilitation—including the utilization of outpatient physical therapy, home health care, skilled nursing facilities, and inpatient rehabilitation facilities—were determined by multiplying the costs associated with each form of rehabilitation¹¹⁸ by the utilization rates as determined by the Healthcare Cost and Utilization Project (HCUP)¹¹⁹ of the U.S. Department of Health & Human Services Agency for Healthcare Research and Quality and from the data of Lombardi et al.⁷⁰. Postoperative medication expenses were determined by applying average medication prices¹¹⁶ to a typical postoperative medication regimen. Expenses for postoperative follow-up were determined using follow-up rates from a survey of joint replacement surgeons¹¹⁷ as well as physician visit and imaging expenses derived from the 2012 Physician Fee Schedule¹¹².

Cost of Complications

The costs of major perioperative medical complications were determined by taking a weighted average of median costs from HCUP data¹¹⁹ multiplied by the frequency of each complication in knee arthroplasty patients as found by Mantilla et al.⁵⁵. Expenses associated with conservative treatment of a suboptimal or failed prosthesis were estimated by multiplying the costs of conservative treatment of severe end-stage osteoarthritis, as determined in a

TABLE IV Distributions Used in Probabilistic Sensitivity Analysis*

Parameter	Distribution
Age	Uniform (50-60)
Probability of early HTO implant failure	Beta (38, 1104)
Probability of late HTO implant failure	Beta (113, 4777)
Probability of early UKA implant failure	Beta (161, 5951)
Probability of late UKA implant failure	Beta (113, 4777)
Probability of early TKA implant failure	Beta (29, 4975)
Probability of late TKA implant failure	Beta (48, 3955)
Probability of failure of HTO converted to TKA	Beta (37, 2261)
Probability of failure of UKA converted to TKA	Beta (37, 2261)
Probability of revision TKA failure	Beta (36, 972)
QALY from optimal primary implant	Normal (0.835, 0.005)
QALY factor for revision TKA†	Uniform (0.87-0.98)

*HTO = high tibial osteotomy, UKA = unicompartmental knee arthroplasty, TKA = total knee arthroplasty, and QALY = quality-adjusted life-year. Early failure = the probability of failure of the implant within one year of the procedure, and late failure = the annual probability of implant failure after one year postoperatively. †Expressed as a multiple of QALYs from an optimal primary implant.

prior study⁶², by 50% because this value could not otherwise be accurately determined.

Distributions

Beta distributions were applied to the probabilities of failure of HTO, UKA, and TKA both within the first postoperative year and annually thereafter. Beta distributions were also applied to the failure rates of revision implants. All beta distributions were determined by examining the number of failed events out of the number of patients in the source studies for the corresponding point estimates listed in Table IV. A normal distribution was applied to the utility derived from primary TKA according to a previously published distribution⁶². Quality of life resulting from a revision TKA was determined by multiplying a factor obtained from a uniform distribution of 87% to 98% by the utility of a primary TKA, which encompassed the range of values from published sources^{21,22,25,64,67,109}. ■

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