The Cost-Effectiveness of Surgical Fixation of Distal Radial Fractures

A Computer Model-Based Evaluation of Three Operative Modalities

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Background: There is no consensus on the optimal fixation method for patients who require a surgical procedure for distal radial fractures. We used cost-effectiveness analyses to determine which of 3 modalities offers the best value: closed reduction and percutaneous pinning, open reduction and internal fixation, or external fixation.

Methods: We developed a Markov model that projected short-term and long-term health benefits and costs in patients undergoing a surgical procedure for a distal radial fracture. Simulations began at the patient age of 50 years and were run over the patient's lifetime. The analysis was conducted from health-care payer and societal perspectives. We estimated transition probabilities and quality-of-life values from the literature and determined costs from Medicare reimbursement schedules in 2016 U.S. dollars. Suboptimal postoperative outcomes were determined by rates of reduction loss (4% for closed reduction and percutaneous pinning, 1% for open reduction and internal fixation, and 11% for external fixation) and rates of orthopaedic complications. Procedural costs were \$7,638 for closed reduction and percutaneous pinning, \$10,170 for open reduction and internal fixation, and \$9,886 for external fixation. Outputs were total costs and quality-adjusted life-years (QALYs), discounted at 3% per year. We considered willingness-to-pay thresholds of \$50,000 and \$100,000. We conducted deterministic and probabilistic sensitivity analyses to evaluate the impact of data uncertainty.

Results: From the health-care payer perspective, closed reduction and percutaneous pinning dominated (i.e., produced greater QALYs at lower costs than) open reduction and internal fixation and dominated external fixation. From the societal perspective, the incremental cost-effectiveness ratio for closed reduction and percutaneous pinning compared with open reduction and internal fixation was \$21,058 per QALY and external fixation was dominated. In probabilistic sensitivity analysis, open reduction and internal fixation was cost-effective roughly 50% of the time compared with roughly 45% for closed reduction and percutaneous pinning.

Conclusions: When considering data uncertainty, there is only a 5% to 10% difference in the frequency of probability combinations that find open reduction and internal fixation to be more cost-effective. The current degree of uncertainty in the data produces difficulty in distinguishing either strategy as being more cost-effective overall and thus it may be left to surgeon and patient shared decision-making.

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

Options for operative fixation of distal radial fractures include closed reduction and percutaneous pinning, open reduction and internal fixation, and external fixation¹. Closed reduction and percutaneous pinning is a less

invasive, inexpensive, and effective technique²⁻⁵; however, some question its capability to consistently achieve and maintain fracture reduction⁶⁻⁸. External fixation is well established but has been associated with high rates of complications, including

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infections and complex regional pain syndrome^{2,9,10}. Open reduction and internal fixation is the most invasive and expensive option, but it is also the most widely used technique^{1,11-13}.

Based on currently available evidence, there is no consensus on the optimal fixation method for distal radial fractures¹⁴. However, there has been a growing trend toward volar locked plating^{1,15,16}. In the literature, the additional costs of open reduction and internal fixation are thought to be offset by more durable fixation¹⁶, shorter periods of immobilization, and earlier return to work, although little evidence supports these claims^{5,13,16}.

To date, cost-effectiveness studies have been conflicting, with 1-year randomized trials finding open reduction and internal fixation to not be cost-effective compared with closed reduction and percutaneous pinning^{12,13}, but a simple 10-year decision tree finding open reduction and internal fixation to cost less and offer more benefits than closed reduction and percutaneous pinning and external fixation¹¹. Given the short time frames, these studies did not account for baseline quality of life or improving quality over time due to healing. Our goal was to utilize a detailed Markov state-transition model to examine the cost-effectiveness of closed reduction and percutaneous pinning, open reduction and internal fixation, and external fixation for the surgical fixation of distal radial fractures over the patients' remaining lifetimes.

Materials and Methods

Analytic Overview

We built a state-transition Markov model for patients with a distal radial fracture that could be treated appropriately with any of 3 methods: closed reduction and percutaneous pinning, open reduction and internal fixation, or external fixation. The model was created using TreeAge Pro (TreeAge Software)¹⁷ and simulates the course of the surgical procedure as a series of transitions between health states over time, dictated by transition probabilities¹⁸. Each health state is characterized by quality of life (utility) and costs. A utility is a measurement of disease burden on a patient's quality of life¹⁹ and is rated on a 0-to-1 scale in which 1 defines a year of perfect health and 0 defines death²⁰. Costs reflect the sum of resources utilized within each health state (both paid and unpaid). Time spent experiencing the utility of each health state is aggregated into quality-adjusted life-years (QALYs). We adhered to recommendations of the Second Panel on Cost-Effectiveness in Health and Medicine and included 2 base cases: a health-care payer perspective that accounts for health-related outcomes and costs, and a societal perspective that also incorporates unpaid caregiver time and productivity costs²⁰. We adhered to reporting guidelines per the Consolidated Health Economic Evaluation Reporting Standards (CHEERS)²¹.

QALYs and costs are incorporated into an incremental cost-effectiveness ratio (ICER), defined as the difference in costs divided by the difference in QALYs between 2 treatments. ICERs quantify the value of a procedure²² and are evaluated in reference to a willingness-to-pay threshold, which is defined as the maximum threshold cost that society is willing to spend for each additional QALY²³. We used the conventional willingness-

to-pay thresholds of \$50,000 and \$100,000²⁴. A treatment is considered cost-effective if its ICER falls below the willingness-to-pay threshold. A treatment is dominated by an alternative if it costs more and produces fewer QALYs than its alternative.

We conducted deterministic and probabilistic sensitivity analyses to evaluate the impact of data input uncertainty on our results. We portrayed the results of these sensitivity analyses in cost-acceptability curves displaying the likelihood that each method would be cost-effective.

Model Structure

Figure 1 shows the structure of the model. Patients enter the model at the time of the initial surgical procedure, after which patients can enter optimal or suboptimal states. The suboptimal category captures patients who have experienced unresolved postoperative orthopaedic complications or inadequate or failed reductions. Orthopaedic complications are grouped into 3 categories: (1) minor complications (superficial pin or wound infections; tenosynovitis or tendinitis), (2) major complications without an additional surgical procedure (complex regional pain syndrome; nonoperative nerve injuries, neuropathies, carpal tunnel syndrome treated conservatively; or early office-based pin or fixator removal), and (3) major complications requiring a surgical procedure (operative nerve injuries, tendon rupture, deep infection, implant failure or removal)²⁵.

Over the initial 6-week cycle, patients with major orthopaedic complications requiring a surgical procedure undergo a revision surgical procedure and can return to the optimal state if they have no additional or persistent complications or can remain in the suboptimal state. Within the first 12 weeks of primary fixation, patients with failed or inadequate reduction within the suboptimal state may undergo an open reduction and internal fixation as a revision procedure. Revision outcomes are also categorized into optimal and suboptimal states. During each 6-week period, patients can die according to their age-stratified mortality. Patients enter the model at 50 years of age on the basis of a literature mean age at presentation^{2-4,10,15,26-30}. In a sensitivity analysis, we conducted age-stratified analysis for 2 age groups, 25 years and 65 years, to evaluate the effect of age on the results.

Transition Probabilities

Following primary fixation, the probability of entering the suboptimal state (compared with the optimal state) was determined by the composite probabilities of reduction loss and postoperative complications (Table I). These data were derived from randomized controlled trials and prospective cohort studies that were identified via a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methods-compliant systematic review of the literature (see Appendix). We determined that a mean of 77% of closed reduction and percutaneous pinning^{2-5,7,27,31}, 67% of open reduction and internal fixation^{5,10,15,29,32-34}, and 63% of external fixation^{2,27,30,32,35-37} procedures with postoperative loss of reduction underwent revisions within 6 weeks and could then enter optimal or suboptimal post-revision states, and that loss of reduction

Fig. 1
General schematic of the Markov model used to evaluate the cost-effectiveness of closed reduction and percutaneous pinning, open reduction and internal fixation (ORIF), and external fixation methods for operatively treated distal radial fractures over 6-week cycles. Patients start the model at the time of the initial surgical procedure and can transition to optimal and suboptimal health states. Patients receiving successful treatment of complications can progress to an optimal state or can remain in a suboptimal state. Patients undergoing a revision surgical procedure for loss of reduction or major (operative) complications can experience optimal and suboptimal health states. Patients not undergoing revision fixation or again experiencing loss of reduction following revision fixation remain with failed fixation (not pictured). Over each 6-week period, patients can remain within their health states or may die from age-adjusted, all-cause mortality (not pictured). Direct arrows indicate transitions between health states; curved arrows indicate stasis within a health state.

occurred at a rate of 4% for closed reduction and percutaneous pinning, 1% for open reduction and internal fixation, and 11% for external fixation. We assumed that the transition probabilities for a revision open reduction and internal fixation would be similar to those of a primary open reduction and internal fixation. We assumed that the risk of perioperative medical complications (e.g., myocardial infarction or stroke) was similar for all 3 procedures and was estimated at 0.8%³⁸. We used annual all-cause mortality rates from United States Life Tables³⁹ and adjusted them to 6-week time frames. Derivations of additional transition probabilities are provided in the Appendix.

Quality of Life

We derived optimal quality-of-life values after 6 weeks and 1 year of fixation from some recent studies (Table I). We used linear interpolation between 6-week and 1-year values. Our model applied time-dependent, quality-of-life differences for

optimal fixations between the 6-week time point (e.g., 0.66 for closed reduction and percutaneous pinning, 0.721 for open reduction and internal fixation, 0.65 for external fixation) and the 1-year period following fracture fixation²⁻⁵, after which we allowed patients to return to their baseline, age-adjusted quality of life⁴⁰. We assumed that the initial disutility of immobilization would be captured by the 6-week quality-of-life values. Patients with suboptimal fixations received a lower composite quality of life based on the method's relative frequency of postoperative complications or reduction loss (Table I). For revision open reduction and internal fixations after closed reduction and percutaneous pinning and external fixation, we estimated that the quality of life lay at the midpoint between that of optimal primary fixation and optimal open reduction and internal fixation⁴¹. Because no data exist on quality of life for revision open reduction and internal fixation after primary open reduction and internal fixation, we assumed a median 7.5% loss of quality of life⁴²⁻⁴⁵. Patients who live with failed fixation were

TABLE I Base Case Input Parameters*

Parameters	Closed Reduction and Percutaneous Pinning	Open Reduction and Internal Fixation	External Fixation
Suboptimal transition probabilities			
Loss of reduction†	4% ^{2,5,7,27,28,31,106,107}	1% ^{3,5,10,15,28-35,37,108-110}	11% ^{2,10,27,29,30,35-37,111-113}
Complications			
Minor‡	11% ^{2,5,7,28,31,70}	7% ^{3,5,7,10,15,29-35,37,109,110,114}	10% ^{2,10,27,29,30,35,37,71-73,112,113,115,116}
Major nonoperative§	10% ^{2,4,5,7,28,31,70,107,117}	12% ^{4,5,7,10,15,28-37,108-110,117}	16% ^{2,10,29,30,35-37,71-73,112,115,116}
Major operative#	6% ^{2,5,27,31,70,106,117}	5% ^{3,5,10,15,29-37,108-110,114,117}	11% ^{10,27,29,32,35-37,71-73,113,115}
Quality of life (utilities)**			
Optimal fixation			
At 6 weeks	0.66 ¹³	0.721 ^{13,35}	0.65 ³⁵
At 1 year	0.862 ¹³	0.854 ^{12,13,35}	0.89 ³⁵
Suboptimal fixation			
Minor or major complication, at 6 weeks	0.560 ^{11-13,92,95,96,98-100,102}	0.615 ^{11-13,35,92,95,96,98-100,102}	0.552 ^{11,35,92,95,96,98-100,102}
Loss of reduction, at 6 weeks	0.618 ^{41,46,47}	0.666 ^{41,46,47}	0.606 ^{41,46,47}
Procedural costs (2016 U.S. dollars)			
Preoperative work-up††	\$252 ⁴⁹⁻⁵¹	\$252 ⁴⁹⁻⁵¹	\$252 ⁴⁹⁻⁵¹
Anesthesia costs	\$129 ^{53,54}	\$173 ^{53,54}	\$152 ^{53,54}
Surgery costs	\$3,443 ^{50,52,118}	\$5,655 ^{50,52,118}	\$5,655 ^{50,52,118}
Surgeon fee	\$696 ^{49,50}	\$874 ^{49,50}	\$611 ^{49,50}
Postoperative care‡‡	\$105 ^{49,50,103}	\$105 ^{49,50,103}	\$105 ^{49,50,103}
Post-acute rehabilitation and physical therapy	\$3,014 ^{49,55,119,120}	\$3,112 ^{49,55,119,120}	\$3,112 ^{49,55,119,120}
Productivity costs (2016 U.S. dollars per day)			
Base case (50 years old)	\$190 ^{56,57}	\$190 ^{56,57}	\$190 ^{56,57}
25 years old	\$147 ^{56,57}	\$147 ^{56,57}	\$147 ^{56,57}
65 years old	\$59 ^{56,57}	\$59 ^{56,57}	\$59 ^{56,57}
Unpaid caregiver costs (2016 U.S. dollars per day)	\$61 ^{56,57}	\$61 ^{56,57}	\$61 ^{56,57}
Time			
Mean time out of work (d)	42 ^{3,13,58}	32 ^{3,13,58}	40 ^{3,13,58}

*When multiple sources of data were available, we pooled data and weighted by sample sizes. We limited our literature to include volar locking plates for open reduction and internal fixation and bridging external fixation with or without supplementary pins for external fixation. †The probability of the fracture to lose reduction within a 6-week period following surgical fixation. ‡The probability of the patient to sustain a minor orthopaedic complication (superficial pin or wound infection, tenosynovitis or tendinitis) within a 6-week period following surgical fixation. §The probability of the patient to sustain a major orthopaedic complication that does not require a revision surgical procedure (complex regional pain syndrome, nonoperative nerve injury or carpal tunnel syndrome, early nonoperative pin or fixator removal) within a 6-week period following surgical fixation. #The probability of the patient to sustain a major orthopaedic complication requiring a revision surgical procedure (tendon rupture, nerve injury or carpal tunnel release, deep infection, or implant removal) within a 6-week period following surgical fixation. **Utility values experienced in each health state after 6-week cycles. Note that, within the model, the optimal values were time-dependent and linearly increased with each 6-week cycle up to the 1-year time period, after which patients received their background quality of life⁴⁰. Suboptimal fixation utilities represent a composite decrement from the corresponding optimal fixation utility based upon the fixation method's relative frequency of complications or reduction loss. ††Preoperative work-up includes the costs of an initial preoperative level-3 visit, preoperative radiographs, routine venipuncture, and laboratory screen for electrolytes, complete blood-cell count, and coagulation factors. ‡‡Postoperative care includes the costs of postoperative analgesia (i.e., 30 doses of 5-mg oxycodone with or without acetaminophen) and post-operative radiographs.

attributed a quality of life of 0.7 given the composite risk of nonunion, malunion, and wrist arthritis^{41,46-48}. Derivations of additional quality-of-life values are provided in the Appendix.

Costs

We used the Medicare reimbursement schedule to estimate unit costs of outpatient visits, imaging, laboratory tests, anesthesia and surgeon fees, surgery-related inpatient and outpatient technical costs, postoperative care and evaluations, medical complications, orthopaedic complication treatments, and postoperative rehabilitation and physical therapy⁴⁹⁻⁵⁵. Frequency of resource use for each treatment was determined from expert surgeon consultation. Costs for revision open reduction and internal fixations were assumed to be equal to those of a primary open reduction and internal fixation.

For the societal perspective, we calculated productivity costs from the age-specific likelihood of labor force participation and mean daily earnings^{56,57} multiplied by mean days out of work^{3,13,58}. We calculated unpaid caregiver time-costs from the mean daily salary of a home health aide^{57,59} multiplied by the mean days out of work^{3,13,58}. Because all methods possess the same annual age-adjusted mortality, we ignored future consumption costs^{20,57}. We expressed costs in 2016 U.S. dollars based on the Consumer Price Index⁶⁰ with a 3% annual discount rate for quality of life and costs.

Sensitivity Analyses

We conducted 1-way and 2-way deterministic sensitivity analyses on all transition probability, quality of life, and time

parameters. We varied transition probabilities and time values (e.g., days out of work) across all possible ranges found in the literature and utilities by 50% above and below base value (see Appendix). The period of time affected by fracture fixation was varied from 1-year to 5-year time frames, utilizing long-term quality-of-life values of 0.94 for closed reduction and percutaneous pinning, 0.96 for open reduction and internal fixation, and 0.93 for external fixation¹¹.

We conducted probabilistic sensitivity analysis to evaluate the uncertainty in all input parameters simultaneously by repeating the cost-effectiveness analysis through 10,000 simulations. In each simulation, the model varied parameters of interest within prespecified beta distributions centered around the base transition probability or quality-of-life value. We used a triangular distribution for the period of time affected by fracture fixation, centered at 1 year and extending to 5 years, and we used a gamma distribution for days out of work to model the uncertainty of societal costs.

Results

Base Case

Patients undergoing these procedures accumulated, after fixation, 13.99 lifetime QALYs for closed reduction and percutaneous pinning, 13.98 lifetime QALYs for open reduction and internal fixation, and 13.89 lifetime QALYs for external fixation (Fig. 2). The mean procedural costs of uncomplicated procedures were \$7,638 for closed reduction and percutaneous pinning, \$10,170 for open reduction and internal fixation, and \$9,886 for external fixation. When considering costs of the

Fig. 2

Bar graph showing an analysis of total QALY outputs from cost-effectiveness analysis of closed reduction and percutaneous pinning (CRPP), open reduction and internal fixation (ORIF), and external fixation (EF) methods, with total QALYs of 13.99 for CRPP, 13.98 for ORIF, and 13.89 for EF. Of note, ORIF has a higher contribution of mean total QALYs from suboptimal fixations (1.68 QALYs, 12%) compared with CRPP because of long-term effects from major (nonoperative) orthopaedic complications, namely, nerve injury not requiring a surgical procedure, neuropathy, and carpal tunnel syndrome treated conservatively. Note that the Y axis begins at 10 QALYs.

Fig. 3

Bar graph showing an analysis of total cost outputs from cost-effectiveness analysis of closed reduction and percutaneous pinning (CRPP), open reduction and internal fixation (ORIF), and external fixation (EF) methods. The total costs from the health-care sector perspective incorporate surgical procedural costs, costs of medical and orthopaedic complications, and costs of revision and failed fixations, with total costs of \$8,735 for CRPP, \$11,125 for ORIF, and \$11,759 for EF. The mean total costs are primarily costs of the procedures themselves: 87.4% for CRPP, 91.4% for ORIF, and 84.1% for EF. Revision fixation procedures following loss of reduction contributed a mean of 3.6% for CRPP and 5.8% for EF, but only 1.0% for ORIF. The total costs from the societal perspective incorporate health-care sector costs from above in addition to costs of lost productivity and costs of unpaid caregiving, with a total of \$19,435 for CRPP, \$19,214 for ORIF, and \$22,295 for EF. From the societal perspective, the costs of lost productivity contributed 41.6% for CRPP and 35.7% for EF, but only 31.8% for ORIF. USD = U.S. dollars.

procedure, complications, and revisions from the health-care payer perspective, the total costs were \$8,735 for closed reduction and percutaneous pinning, \$11,125 for open reduction and

internal fixation, and \$11,759 for external fixation (Fig. 3). From this perspective, closed reduction and percutaneous pinning produces greater QALYs and fewer costs than both open

TABLE II Results of Base Case Cost-Effectiveness Analysis Among the Three Fixation Methods for Operative Distal Radial Fractures from Health-Care Sector and Societal Perspectives*

Perspective and Methods	Total QALYs	Total Costs	ICER (\$/QALY)
Health-care sector perspective			
Closed reduction and percutaneous pinning	13.99	\$8,735	Reference
Open reduction and internal fixation	13.98	\$11,125	Dominated
External fixation	13.89	\$11,759	Dominated
Societal perspective			
Open reduction and internal fixation	13.98	\$19,214	Reference
Closed reduction and percutaneous pinning	13.99	\$19,435	\$21,058
External fixation	13.89	\$22,295	Dominated

*An intervention is dominated when it costs more and produces fewer QALYs than a comparative reference intervention.

Fig.4-A

Fig.4-B

Figs. 4-A and 4-B Two-way deterministic sensitivity analysis demonstrating the preferred fixation method when simultaneously varying 2 variables at a given willingness-to-pay (WTP) threshold from the health-care and societal perspectives. CRPP = closed reduction and percutaneous pinning and ORIF = open reduction and internal fixation. **Fig. 4-A** Sensitivity analysis of the rates of reduction loss for CRPP and ORIF. At the base case, the loss of reduction rate was 4.1% for CRPP and 1.4% for ORIF. **Fig. 4-B** Sensitivity analysis of the rates of major (nonoperative) complications for CRPP and ORIF. Base case: CRPP major (operative) complication rate = 10.5% (5.2% nonoperative nerve injury, neuropathy, or carpal tunnel syndrome; 5.3% complex regional pain syndrome); and ORIF major (nonoperative) complication rate = 11.7% (9.7% nonoperative nerve injury, neuropathy, or carpal tunnel syndrome; 2.0% complex regional pain syndrome).

reduction and internal fixation and external fixation and therefore dominates both alternatives. From a societal perspective, open reduction and internal fixation costs the least at

\$19,214 compared with \$19,435 for closed reduction and percutaneous pinning and \$22,295 for external fixation (Fig. 3). The ICER for closed reduction and percutaneous pinning

Fig. 5

Heat index indicating the preferred method between closed reduction and percutaneous pinning (CRPP) (blue) or open reduction and internal fixation (ORIF) (yellow) based on the willingness-to-pay threshold when varying the difference in numbers of days out of work between CRPP and ORIF. When the ICER for CRPP crosses the willingness-to-pay threshold (white), the preference switches to ORIF. Stricter budgetary considerations or higher valuations of productivity (i.e., lower willingness to pay) correspond to a smaller tolerable difference in days out of work between CRPP and ORIF.

compared with open reduction and internal fixation is \$21,058 per QALY, below the willingness-to-pay threshold of \$50,000. From this perspective, because external fixation is costlier (\$22,295) and produces fewer QALYs than both closed reduction and percutaneous pinning and open reduction and internal fixation, it remains dominated (Table II).

Sensitivity Analyses

Figure 4-A illustrates the sensitivity of the results to reduction loss after closed reduction and percutaneous pinning and open reduction and internal fixation. From the health-care sector perspective and willingness-to-pay threshold of \$100,000, open reduction and internal fixation only becomes preferred (defined as the cost-effective or dominant option) if reduction loss after closed reduction and percutaneous pinning increases from the base value of 4% to 16%. All other things being equal, even if open reduction and internal fixation reduction loss is 0%, closed reduction and percutaneous pinning is still pre-

ferred unless the reduction loss after closed reduction and percutaneous pinning exceeds roughly 14%. The societal perspective is less tolerant of reduction loss: the rate of reduction loss after closed reduction and percutaneous pinning would have to exceed only 5% at a willingness-to-pay threshold of \$50,000, or 6.5% at a willingness-to-pay threshold of \$100,000, for open reduction and internal fixation to become preferred.

Figure 4-B illustrates the sensitivity of the results to major (nonoperative) complications of closed reduction and percutaneous pinning and open reduction and internal fixation. From a health-care sector perspective and willingness-to-pay threshold of \$100,000, open reduction and internal fixation is preferred if its combined complication rate reduces from roughly 12% to 10%. The societal perspective is more sensitive to this value: if the open reduction and internal fixation base complication rate decreases by roughly 0.5%, then open reduction and internal fixation is preferred at the \$50,000 and \$100,000 willingness-to-pay thresholds.

Fig.6-A

Fig.6-B

Figs. 6-A and 6-B Cost-effectiveness acceptability curves showing the percentage of the 10,000 probabilistic sensitivity analysis runs (see Appendix) that demonstrated cost-effectiveness across various willingness-to-pay thresholds. CRPP = closed reduction and percutaneous pinning, EF = external fixation, and ORIF = open reduction and internal fixation. **Fig. 6-A** The acceptability curve from the health-care perspective incorporating uncertainty around multiple parameters: probability of reduction loss, probability of major (nonoperative) complications, probability of plate removal for tendinitis after ORIF, quality of life 1 year after optimal fixation, and the period of time affecting the quality of life after the fracture and its fixation. **Fig. 6-B** The acceptability curve from the societal perspective incorporating the additional uncertainty around the number of days out of work for each fixation method.

When the days out of work are equal between closed reduction and percutaneous pinning and open reduction and internal fixation, closed reduction and percutaneous pinning is preferred at both willingness-to-pay thresholds (Fig. 5). The \$50,000 willingness-to-pay threshold requires patients undergoing open reduction and internal fixation to miss approximately 12 fewer days of work for open reduction and internal fixation to be preferred. The \$100,000 willingness-to-pay threshold requires an approximate difference of 14 days for open reduction and internal fixation to be preferred.

Age-Stratified Analysis

For a cohort of 25-year-old patients, closed reduction and percutaneous pinning dominated open reduction and internal fixation from a health-care sector perspective, producing greater QALYs (21.19 compared with 21.17) at a lower cost (\$8,689 compared with \$11,082). From the societal perspective, closed reduction and percutaneous pinning remained the dominant option, with the same QALY differential at a lower total cost (\$17,480 compared with \$17,772). For an older 65-year-old cohort, open reduction and internal fixation resulted in greater QALYs than closed reduction and percutaneous pinning (9.55

compared with 9.54) at a higher cost (\$11,124 compared with \$8,733), generating an ICER of \$384,695/QALY, which is above the willingness-to-pay thresholds of \$50,000 and \$100,000. From the societal perspective, open reduction and internal fixation resulted in the same QALY differential for a higher cost (\$14,998 compared with \$13,857), resulting in an ICER of \$200,786, which is also above the willingness-to-pay thresholds.

Probabilistic Sensitivity Analysis

Figures 6-A and 6-B depict cost-effectiveness acceptability curves. In Figure 6-A, from the health-care sector perspective, open reduction and internal fixation has the greatest proportion of cost-effectiveness across a higher willingness to pay compared with closed reduction and percutaneous pinning and external fixation, although the gap between open reduction and internal fixation and closed reduction and percutaneous pinning is small. In Figure 6-B, from the societal perspective, open reduction and internal fixation is the more cost-effective method at even lower willingness to pay. However, there is only a 5% to 10% difference in frequency of combinations that find open reduction and internal fixation to be more cost-effective.

Discussion

We investigated the cost-effectiveness of closed reduction and percutaneous pinning, open reduction and internal fixation, and external fixation for operative distal radial fractures. From the health-care sector perspective, accounting for total medical costs paid by third-party payers and patients out-of-pocket²⁰, closed reduction and percutaneous pinning was both the cheapest and most effective option. From the societal perspective, including lost productivity and unpaid caregiving, open reduction and internal fixation was the least costly procedure, but closed reduction and percutaneous pinning demonstrated greater effectiveness and was cost-effective, with an ICER of \$21,058 per QALY. However, variations around certain parameters (e.g., rates of reduction loss and nonoperative complications) make it difficult to distinguish closed reduction and percutaneous pinning from open reduction and internal fixation with great certainty across all scenarios. From both perspectives, external fixation as the definitive treatment was the costliest and least effective.

As earlier studies have suggested^{5,13,16}, our results, considering the costs of lost productivity while out of work and of unpaid caregiving while immobilized, support open reduction and internal fixation as the least costly technique. In our model, the benefit in terms of earlier return to work after open reduction and internal fixation compared with closed reduction and percutaneous pinning was 10 days. However, the reported range of difference varies from 9 to 28 days^{3,13,61,62}. Depending on the patient age and occupation and the value of earnings lost, a faster return to work could favor open reduction and internal fixation over closed reduction and percutaneous pinning in situations with high monetary cost of being out of work.

Despite documented efficacy^{3-5,26,63}, closed reduction and percutaneous pinning has been associated with an inferior ability to achieve and maintain reduction^{2,7,8,64}, with total complication rates as high as 30% to 50%⁶⁵⁻⁶⁷. Our model estimated more

modest but still comparatively higher rates of reduction loss, minor complications, and major complications requiring a surgical procedure after closed reduction and percutaneous pinning compared with open reduction and internal fixation. However, open reduction and internal fixation had a higher rate of major nonoperative complications compared with closed reduction and percutaneous pinning, owing mainly to a higher rate of non-operatively treated nerve injury or neuropathy. A background rate of neuropathy is associated with distal radial fractures from compression by hematoma, osseous fragments, or soft-tissue swelling⁶⁸, but some studies have noted rates of mild to moderate median, radial, or ulnar nerve dysfunction ranging from 10% to 40% following open reduction and internal fixation^{5,29,35,69}. The longitudinal disutility conferred by these complications drives the lower total quality of life for open reduction and internal fixation compared with closed reduction and percutaneous pinning in the base case and in the younger 25-year-old cohort. Lowering the open reduction and internal fixation rate of non-operatively treated nerve injury, neuropathy, or complex regional pain syndrome by just 2% shifts the cost-effectiveness results in favor of open reduction and internal fixation. Likewise, higher valuations of productivity from the societal perspective are less tolerant of closed reduction and percutaneous pinning reduction loss of >5% given the additional costs of revision fixation.

When considering data uncertainty, there is only a 5% difference in the frequency of probability combinations that find open reduction and internal fixation to be more cost-effective from the societal perspective. The current degree of uncertainty in the data produces difficulty in distinguishing either strategy as being more cost-effective overall and thus it may be left to the surgeon's experience and judgment per patient preferences, circumstances, and outcomes. Our model provides evidence-based reference ranges under which either open reduction and internal fixation or closed reduction and percutaneous pinning would be preferred, and these could be used as an aid in shared decision-making.

Our results are to be viewed in light of some limitations. The lack of published data necessitated assumptions in certain transition probabilities and utilities, as described in the Materials and Methods section and the Appendix⁷⁰⁻¹⁰⁵. It is not clear whether QALYs are sensitive enough to detect differences between fixation methods for distal radial fractures; there is a need for greater study into preference-based outcomes. The sensitivity analyses in this study reflect the uncertainty and inconsistency in the data and have been incorporated into the conclusions. Inherent to the trade-offs in decision analytic methodology, we assumed that the probability of sustaining a minor or major complication and a loss in reduction were mutually exclusive. We limited our data to studies that attempted to randomize across fracture types (e.g., intra-articular compared with extra-articular, degree of comminution) to avoid confounding. We acknowledge that specific distal radial fractures inherently require certain treatment; for example, partial articular fractures with a volar shearing mechanism requiring open buttress plating. Our findings cannot be applied to all injuries without clinical judgment. We acknowledge that lost productivity is a

complex concept that is not fully captured by the valuation of age-stratified mean daily earnings lost; more granular methods of valuation and more comprehensive evaluation of age-related effects are needed for future studies.

Previous cost-effectiveness studies of distal radial fracture fixation have been conflicting¹¹⁻¹³. Our study found that closed reduction and percutaneous pinning did have the highest likelihood of being cost-effective given a reduction loss rate of <5%, a combined rate of complex regional pain syndrome and non-operatively treated nerve injury or neuropathy after open reduction and internal fixation of >10%, and a 10-day delay in return to work for closed reduction and percutaneous pinning compared with open reduction and internal fixation. However, given historical inconsistency with regard to these parameters, it is difficult to distinguish open reduction and internal fixation or closed reduction and percutaneous pinning as the more cost-effective alternative in all scenarios, especially given the cost benefit provided by open reduction and internal fixation from shorter immobilization and faster return to work. We recommend that future studies work toward clarifying the extent of nonoperatively treated nerve injury, neuropathy, and complex regional pain syndrome following a distal radial fracture surgical procedure and their effects on quality of life. Randomized controlled trials with longer follow-up periods can assist in a better understanding of the long-term effects of surgical fixation of distal radial fractures.

Appendix

Descriptions of methodologies for the systematic review, transition probabilities, quality of life, costing, and analyses

for quality-of-life sensitivity and probabilistic sensitivity, as well as figures showing scatterplots of probabilistic sensitivity analyses from the health-care perspective and the societal perspective, are available with the online version of this article as a data supplement at [jbjs.org \(http://links.lww.com/JBJS/E600\)](http://links.lww.com/JBJS/E600). ■

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