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Original Article

Establishing Age-Specific Cost-Effective Annual Revision Rates for Unicompartmental Knee Arthroplasty: A Meta-Analysis

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ABSTRACT

Background: Improved survivorship has contributed to the increased use of unicompartmental knee arthroplasty (UKA) as an alternative to total knee arthroplasty (TKA) for unicompartmental knee osteoarthritis. However, heterogeneity among cost-effectiveness analysis studies comparing UKA to TKA has prevented the derivation of discrete implant survivorship targets. The aim of this meta-analysis was to determine the age-stratified annual revision rate (ARR) threshold for UKA to become consistently cost-effective for unicompartmental knee osteoarthritis.
Methods: A systematic search was performed for cost-effectiveness analysis studies of UKA vs TKA. Selected publications were rated by evidence level and assessed for methodological quality. Target UKA survivorship values determined by sensitivity analysis were retrieved, converted to ARR, and combined by age category (<65, 65-74, and ≥75 years) to estimate age-specific cost-effectiveness thresholds.
Results: Four studies met all inclusion criteria. All publications were evidence level I-B, with high methodological quality. Combined data indicated median threshold cost-effective ARR of 1.471% (interquartile range [IQR], 1.415-1.833; age <65), 1.135% (IQR, 1.011-1.260; age 65-74), and 1.760% (IQR, 1.660-2.880; age ≥75). Current revision rates are already below the cost-effective threshold for patients aged ≥75, but exceed recommended values in younger patients.
Conclusion: The findings indicate that implant survivorship is a limiting factor toward achieving cost-effective UKA in patients aged <65. Strategies to improve UKA survivorship, such as shifting procedures to high-volume centers, may render UKA cost-effective in younger patients. This presents an opportunity for resource reallocation within health systems to achieve cost-effective utilization of UKA across a broader population segment.

Identifying cost-effective surgical alternatives for the same clinical condition is important in the era of value-based healthcare [1,2]. This is apparent in the scenario of unicompartmental knee osteoarthritis (OA). Multiple cost-effectiveness analysis (CEA) studies have evaluated the trade-off between the clinical benefits and higher downstream failure risk of unicompartmental knee arthroplasty (UKA) vs total knee arthroplasty (TKA) [3-10]. UKA is associated with decreased recovery time and complication risk, increased range of motion (ROM), and preserved native kinematics compared to TKA [11-13]. However, TKA offers greater long-term implant survivorship [5,14]. In such studies, implant survivorship has consistently represented one of the key determinants of relative cost-effectiveness between the 2 procedures [3-6]. This is not surprising, given the significant financial and health-related consequences of implant failure [4-6].

Improvements in UKA implant survivorship have contributed to its increased use as an alternative to TKA [11,15]. However, optimal

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utilization levels for UKA continue to be a subject of debate [5]. In an increasingly cost-conscious healthcare environment, establishing cost-effective performance targets is important and may guide future utilization trends. To date, however, derivation of such targets with respect to implant longevity has not been possible. Findings from available CEA studies have differed significantly due to heterogeneous assumptions, inputs, and model structures [16]. Additionally, studies have differed in their expression of implant survivorship (ie, cumulative revision vs annual revision rate [ARR]), preventing direct comparison [3-6,8,9].

The purpose of this study was to synthesize findings from existing CEA studies to reach generalizable and actionable UKA implant survivorship goals from an economic perspective. We performed a meta-analysis using sensitivity analysis thresholds to determine age-specific ARR necessary for UKA to become the preferred cost-effective strategy for unicompartmental knee OA.

Methods

Overview

Economic decision models analyze cost-effectiveness on the basis of actual data (base case) and examine the effect of varying each model input in isolation (sensitivity analysis). During sensitivity analysis, individual parameters are increased or decreased (all other parameters are held constant) until the cost-effective strategy changes against a predetermined willingness to pay (WTP). The value at which this occurs is referred to as the threshold (Fig. 1).

The outcome of interest extracted from individual CEA studies was the threshold revision rate of UKA. This represents the highest possible revision rate before UKA ceases to be cost-effective due to the increased costs and decreased utility associated with implant revision. Threshold values are mathematical projections incorporating the unique assumptions, inputs, and structure inherent to each decision model. We statistically combined threshold values from individual studies (grouped by simulated cohort age) to derive target revision rates for cost-effective UKA use in patients aged <65, 65-74, and ≥75 years. Target values were then compared to actual revision rates from publicly available registry data to evaluate whether UKA presently meets survivorship goals for cost-effective implementation.

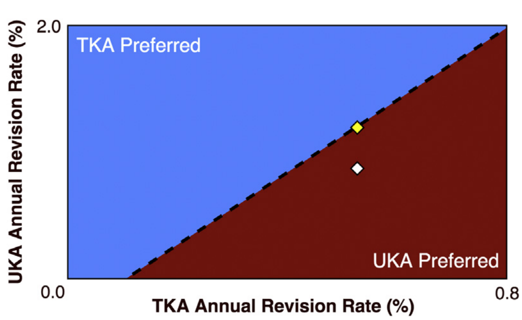

Fig. 1. Threshold annual revision rate schematic. The figure shows the outcome of interest. The x-axes and y-axes represent parameters (implant survivorship in this example) that are varied during sensitivity analysis. The dashed line represents the cost-effective frontier at a $50,000/QALY willingness to pay (WTP). The white diamond represents the base case or actual value used in the model. The gold diamond at the cost-effectiveness frontier represents the threshold value. The threshold is a mathematical projection based on the other inputs and assumptions of each individual decision model. Above this value, the incremental cost-effectiveness ratio of UKA exceeds WTP and it ceases to be cost-effective. This was the value extracted from each study. TKA, total knee arthroplasty; UKA, unicompartmental knee arthroplasty; QALY, quality-adjusted life year.

Search Strategy

A systematic literature search was performed in the PubMed, Embase, and Cochrane Library databases on February 4, 2016, for CEA studies focused on unicompartmental knee OA treatment (Fig. 2). Search terms were "([unicompartmental OR unicondylar OR UKA OR UKR] AND [cost] AND [effectiveness OR utility OR analysis OR evaluation])." Results were filtered to include only English-language studies, yielding a total of 89 publications following the removal of duplicates. Two authors independently screened studies by title and abstract against the inclusion criteria. Disagreements were discussed until consensus was reached. Studies selected underwent full-text review against these criteria, during which reference lists were also scanned for eligible studies.

Inclusion criteria were as follows: (1) CEA studies comparing UKA to TKA, (2) analysis conducted for the United States fee-for-service healthcare system, (3) analysis conducted over a lifetime horizon, (4) costs reported in US dollars, (5) incremental cost-effectiveness ratios reported, and (6) ran deterministic sensitivity analysis to identify a threshold failure rate for UKA to be cost-effective.

Quality Assessment

Critical appraisal of all studies was performed, per the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions [16]. Publications were rated by level of evidence as defined by the Oxford Center for Evidence-Based Medicine [17]. The methodological quality of each study was evaluated using (1) the Quality of Health Economic Studies (QHES) instrument and (2) the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) statement [18-20]. The former awards a weighted numerical score out of 100 possible points based on 16 binary criteria. Studies scoring above 80 are typically designated as high quality [20]. The latter is a qualitative, yet more recent, assessment reflecting 24 items considered essential for standardized reporting of health economic data [18,21]. Numeric CHEERS scores were generated for all studies, with one point assigned for each criterion satisfied and one-half point per partially satisfied criterion. Study heterogeneity and risk of bias are incorporated in these rating systems.

Data Collection

We extracted the cost-effective UKA survivorship threshold from each CEA study selected for inclusion. As detailed above, threshold values do not represent actual revision rates (which are incorporated in the base case analysis). Rather, they are theoretical limits calculated from the interaction of multiple inputs and assumptions unique to each decision model. Threshold revision rates represent the highest possible revision rate at which UKA remains cost-effective below a designated WTP. These values are derived by deterministic sensitivity analysis, the results of which are reported by each study.

Threshold revision rates were directly obtained or mathematically derived from each selected CEA study. Where necessary, these values were converted to ARR, expressed as the percentage of implants revised per observed component-year. ARR was chosen on the basis of superior statistical accuracy for survivorship comparison, as it corrects for variable follow-up periods [14,22]. For studies that performed CEA across different age-groups, ARR values were retrieved individually from each cohort and considered to be separate data points for analysis.

We used a $50,000/QALY (quality-adjusted life year) WTP limit to define cost-effectiveness. While the validity of the $50,000/QALY WTP remains subject to debate, it was the most common standard against which studies established cost-effectiveness during sensitivity analysis and was therefore retained [2].

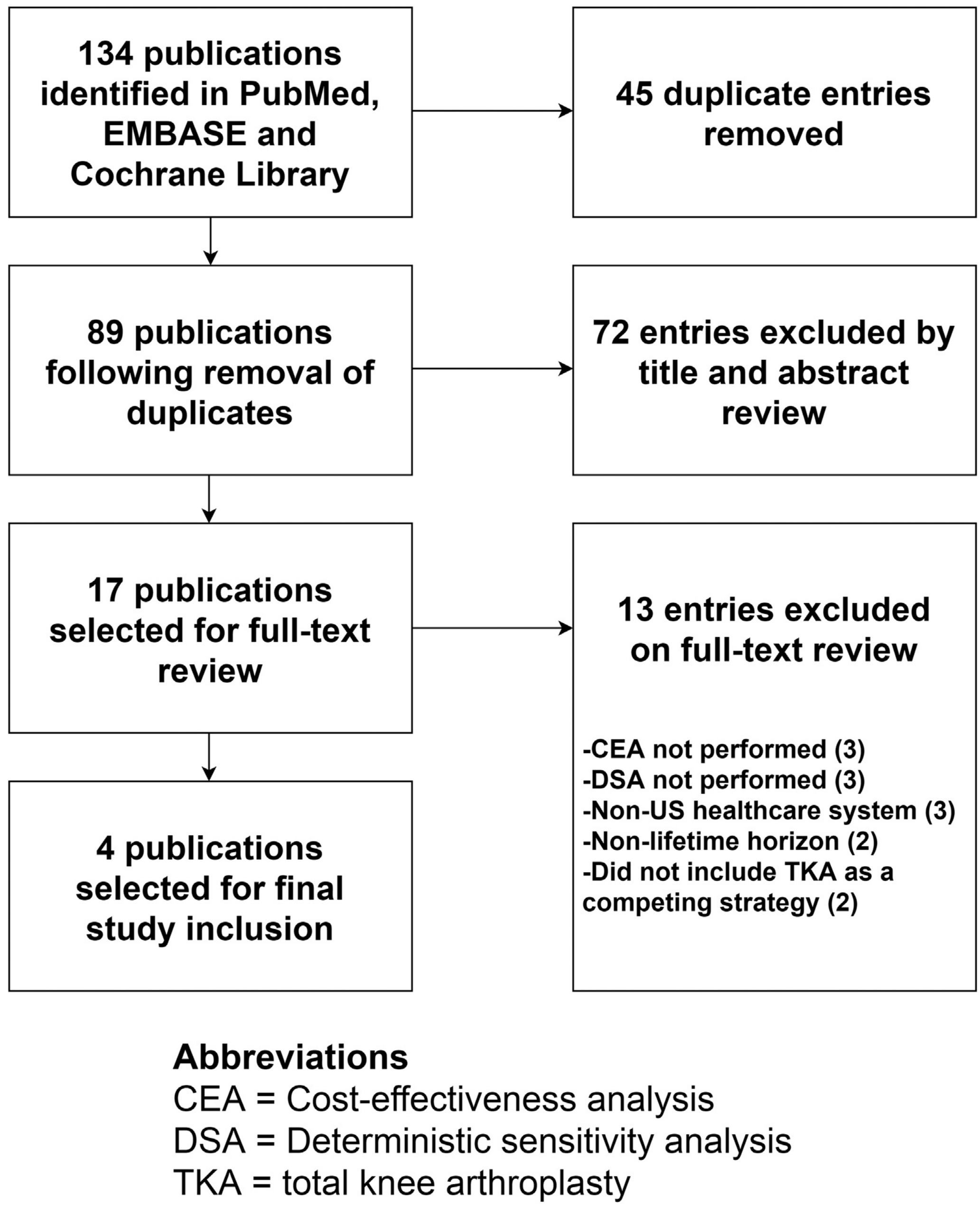

Fig. 2. Systematic search algorithm. This depicts the search algorithm for retrieving publications for inclusion, which was performed in accordance with the PRISMA guidelines.

Statistical Analysis

Having identified individual threshold ARR for cost-effective UKA from individual studies, we statistically combined these point values to derive overall target revision rates. First, 3 age categories were defined based on the convention used by national registries (<65, 65-74, and ≥75) [22-25]. Threshold ARR values derived from each study (or trial cohort within a single study) were assigned to one of these age categories, based on the age specified for the simulated model cohort. Three age-based data series were therefore created, each consisting of individual threshold revision rates derived from different CEA studies.

Next, we generated age-based ARR thresholds from the data points within each series. For each age category, the median of individual threshold ARR values was used as the combined target revision rate. Three overall target revision rates were generated in this manner, one for each of the age categories detailed above. All individual data points were weighted equally, as economic decision models do not incorporate a defined sample size. Due to the small number of published studies, median was selected as the most statistically robust measure of central tendency. Sample variability for each age-based target revision rate was expressed using the interquartile range (IQR) of the data points used to calculate the corresponding median. Box and whisker plots were generated (Excel 2008, Microsoft Inc, Redmond, WA) to depict this variability.

Clinical Data Comparison

We sought to assess the degree to which UKA currently meets (or fails to meet) the cost-effective survivorship targets derived from CEA projections. In the absence of a centralized American arthroplasty registry, no single source provides the data to make

Table 1
Included Cost-Effectiveness Analyses of UKA vs TKA, Stratified by Age.

Author	Year	Cohort Age	Source of Failure Rates	ICER ($/QALY)	Preferred Intervention
Soohoo et al [3]	2006	65	1 RCT, 6 prospective, 2 retrospective (1 registry-based)	277 (UKA/TKA)	UKA
Slover et al [4]	2006	78	Norwegian Registry 1987-2003	UKA dominates	UKA
Ghomrawi et al [5]	2015	45	Swedish Registry 2012	30,300 (TKA/UKA)	TKA
Ghomrawi et al [5]	2015	55	Swedish Registry 2012	63,000 (TKA/UKA)	UKA
Ghomrawi et al [5]	2015	65	Swedish Registry 2012	UKA dominates	UKA
Ghomrawi et al [5]	2015	75	Swedish Registry 2012	UKA dominates	UKA
Ghomrawi et al [5]	2015	85	Swedish Registry 2012	UKA dominates	UKA
Konopka et al [6]	2015	55	1 RCT, 2 prospective, 6 retrospective (2 registry-based)	12,400 (TKA/UKA)	TKA

Preferred intervention was assessed against a $50,000 per QALY willingness to pay threshold.
UKA, unicompartmental knee arthroplasty; TKA, total knee arthroplasty; RCT, randomized controlled trial; ICER, incremental cost-effectiveness ratio; QALY, quality-adjusted life year.

this judgment. We therefore compared our target revision rates to actual revision rates from 4 publicly available national registries (UK, NZ, Australian, and Swedish). Taken together, these registries show the range of actual UKA revision rates that can be compared to the above threshold revision rates.

Registry ARR were derived from age-specific cumulative revision rates, assuming a constant failure rate. We reported the proportion of registry values within the IQR calculated for each age-based threshold. This represents the likelihood that actual UKA revision rates overlap with the middle 50th percentile of cost-effective thresholds identified by existing CEA studies. All statistical analyses were performed using SPSS version 21 (SPSS Inc, IBM Corporation, Armonk, NY).

Results

Search Results

A total of 17 publications underwent full-text review. Four studies, representing 8 trial cohorts, were selected for final inclusion (Table 1). UKA was the preferred strategy in 6 of the 8 cohorts in the base case (Table 1) [3-6]. Below we describe these studies in chronological order, detailing specific methods to extract cost-effective threshold ARR values from sensitivity analysis data.

Soohoo et al, 2006

The study evaluated the lifetime cost-effectiveness of UKA vs TKA in patients aged 65 years, assuming an 18-year postoperative life expectancy [3]. The authors reported that UKA is cost-effective at an overall implant longevity within 3 to 4 years of TKA [3]. UKA was assumed to provide 12 years of full function (compared to 15 years for TKA) during sensitivity analysis, after which all implants were assumed to fail [3]. As such, the model did not incorporate an annual risk of implant failure. It was therefore necessary to calculate this on the basis of the sources cited in the study, using the following method.

The study was reviewed to identify the source informing the assumption that TKA provides 15 years of function before implant failure. The cited source was a review article, featuring a section titled “Clinical Results of TKA [26].” All publications referenced in this section were retrieved and reviewed [27-39]. The total number of implants, number of revisions, and mean follow-up period of each referenced study were recorded in a spreadsheet (Excel 2008, Microsoft Inc, Redmond, WA). Total observed component-years for each study were calculated as the product of the total number of implants and the mean follow-up duration. The total number of failures and total observed component-years were pooled and divided to yield the weighted ARR of TKA [40] (Table 2). An overall TKA implant survival time of 116.92 years was extrapolated from the resulting value of 0.855%. The cost-effective threshold implant lifespan of UKA was estimated by subtracting 4 years (yielding 112.92 years), as specified by the conclusions of the study [3]. This translated to a maximum ARR of 0.886% for UKA to remain cost-effective.

Slover et al, 2006

The study evaluated the lifetime cost-effectiveness of UKA vs TKA in patients aged 78 years, using comparative survivorship data from the Norwegian Joint Registry [4]. Sensitivity analysis revealed the cost-effective ARR threshold for UKA to be 4.0% [4].

Ghomrawi et al, 2015

The study evaluated the lifetime cost-effectiveness of UKA vs TKA in patients aged 45, 55, 65, 75, or 85 years using a $100,000/QALY WTP threshold [5]. Two modifications were made to the

Table 2
Studies Included in Pooled Analysis of Base Case Total Knee Arthroplasty Annual Revision Rate for Soohoo et al [3].

Author	Year	Initial Cohort	Lost to F/U	Final Cohort	Revised	Mean F/U	Failure (%)	OCY	ARR
Fetzer	2002	101	23	78	1	10.5	1.3	819.0	0.12
Rand[a]	2003	11,606	0	11,606	708	5.9	6.1	68,475.4	1.03
Murty	2003	36	0	36	3	10.0	8.3	360.0	0.83
Faris[a]	2003	536	0	536	79	5.7	14.7	3055.2	2.59
Bhan	2003	50	0	50	2	4.5	4.0	225.0	0.89
Morgan-Jones	2003	75	0	75	1	2.5	1.3	187.5	0.53
Forster[a]	2003	5950	0	5950	208	6.1	3.5	36,295.0	0.57
Gill[b]	2004	1033	0	1033	31	10.0	3.0	10,330.0	0.30
Meding	2004	220	8	212	12	10.2	5.7	2162.4	0.55
Goldberg[b]	2004	124	11	113	15	14.0	13.3	1582.0	0.95
Mahoney[b]	2004	183	0	183	9	10.7	4.9	1958.1	0.46
Illgen	2004	112	58	54	5	10.1	9.3	545.4	0.92
Barrack[b]	2004	158	19	139	6	2.0	4.3	278.0	2.16

F/U, follow-up; OCY, observed component-years (final cohort multiplied by mean follow-up); ARR, annual revision rate (percentage of revisions per OCY).
[a] Mean follow-up length approximated from survivorship table.
[b] Mean follow-up length not provided, used range minimum.

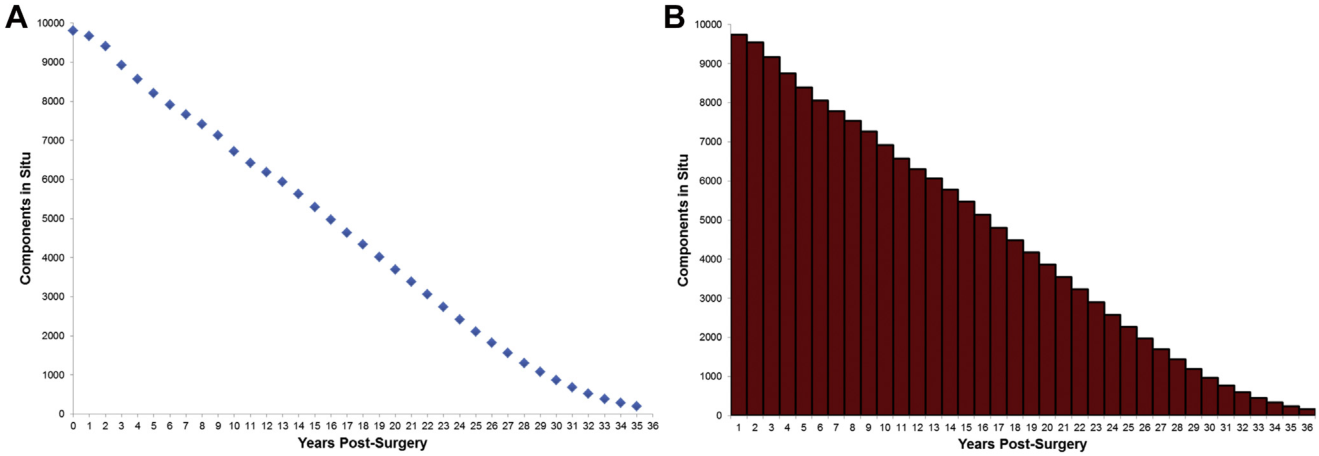

Fig. 3. (A) UKA survivorship curve (B) Integrated survivorship curve. The figure illustrates the mathematical method used to convert implant failure probabilities to annual revision rates (refer to Appendix for full description).

original decision-analytical model (TreeAge Pro 2015, TreeAge Software Inc, Williamstown, MA), which was provided by the authors of the study, to permit direct comparison with the other studies. First, the WTP threshold was recalibrated to $50,000/QALY. Second, UKA survivorship (expressed in the original study as annual failure probability) was recalculated as ARR percentages (Fig. 3) (Appendix). Following these modifications, sensitivity analysis yielded threshold ARR values of 1.358% (age 45), 1.471% (age 55), 1.384% (age 65), 1.560% (age 75), and 1.760% (age 85). Each cohort value was considered to be a separate data point and assigned to a corresponding age category individually.

Konopka et al, 2015

The study evaluated the cost-effectiveness of UKA vs TKA and high tibial osteotomy in patients with a mean age of 55 years [6]. While the authors used WTP thresholds of both $100,000 and $50,000/QALY, only the results of the former were explicitly stated [6]. The cost-effective ARR threshold for UKA vs TKA was estimated from the 2-way sensitivity analysis graph of UKA vs TKA and high tibial osteotomy, using digital measurement along the $50,000 per QALY boundary between UKA and TKA. UKA ARR was 2.32% in the base case, with cost-effective status achieved below 2.194% at a $50,000 per QALY WTP [6].

Quality Assessment

All studies were classified as evidence level I-B. The methodological quality was high, with studies receiving a mean QHES score of 84.75 (range, 83-90; Table 3). The mean proportion of CHEERS criteria fulfilled was 83.7% (range, 82.6-84.8; Table 4). None of the studies explicitly stated the relevant aspects of the system within which decisions are made (ie, geographic and hospital setting).

Combined Age-Based Cohorts

The recommended cost-effective ARR thresholds were 1.471% (IQR, 1.415-1.833) for patients aged <65, 1.135% (IQR, 1.011-1.260) for patients aged 65-74, and 1.760% (IQR, 1.660-2.880) for patients aged ≥75 years. These values represent the median of each age-based data series, which drew data points from the sensitivity analysis results of individual CEA studies (Table 5).

Discussion

The aim of this meta-analysis was to determine the age-stratified ARR that UKA must achieve to become the cost-effective intervention for unicompartmental knee OA. The findings indicate target cost-effective ARR values of 1.471% (<65 years),

Table 3
Quantitative Assessment: Quality of Health Economic Studies Instrument.

Item	Description	Soohoo	Slover	Ghomrawi	Konopka
1	Study objective presented in a clear, specific, and measurable manner	Yes	Yes	Yes	Yes
2	Stated study perspective and rationale	No	No	No	No
3	Data obtained from best available sources	Yes	Yes	Yes	Yes
4	Groups were prespecified at the beginning of the study if data were obtained from subgroup analysis	Yes	Yes	Yes	Yes
5	Used statistical methods and sensitivity analysis to address uncertainty	Yes	Yes	Yes	Yes
6	Performed incremental analysis between competing interventions	Yes	Yes	Yes	Yes
7	Stated methods used for data abstraction	Yes	Yes	Yes	Yes
8	Time horizon appropriate for all relevant outcomes, with discount rate of 3%-5% used and justified	No	Yes	No	No
9	Cost estimation methodology and values clearly described and appropriate	Yes	Yes	Yes	Yes
10	Primary outcome measure(s) clearly stated and justified	Yes	Yes	Yes	Yes
11	Health outcome measures valid and reliable	Yes	Yes	Yes	Yes
12	Model, study methods and analysis and components of numerator and denominator stated clearly and transparently	Yes	Yes	Yes	Yes
13	Choice of economic model, assumptions, and study limitations stated and justified	Yes	Yes	Yes	Yes
14	Stated direction and magnitude of potential biases	No	No	No	No
15	Conclusions justified and based on study results	Yes	Yes	Yes	Yes
16	Stated source of funding for study	Yes	Yes	Yes	Yes
	Scaled score (maximum 100)	83	90	83	83

Scoring is binary, with 0 points awarded for partially fulfilled criteria (ie, stated model perspective or discount rate but did not provide justification).

Table 4
Qualitative Assessment: Consolidated Health Economic Evaluation Reporting Standards Criteria.

Item	Description	Soohoo	Slover	Ghomrawi	Konopka
1	Identifies study as an economic evaluation	Yes	Yes	Yes	Yes
2	Provides structured summary of objectives, perspective, setting, methods, results, and conclusions	Yes	Yes	Yes	Yes
3	Explicitly states broader context for study	Yes	Yes	Yes	Yes
4	Describes characteristics of base case population and subgroups, including rationale for why they were chosen	Partial	Yes	Yes	Yes
5	States relevant aspects of system(s) within which decision(s) are made	No	No	No	No
6	Describes study perspective and relates this to costs being evaluated	Yes	No	Partial	Partial
7	Describes interventions being compared and provides rationale for why they were chosen	Yes	Yes	Yes	Yes
8	States time horizon for costs and effectiveness and provides rationale for why this is appropriate	Yes	Partial	Partial	Partial
9	Reports discount rate for costs and effectiveness and provides rationale for why this is appropriate	Yes	Yes	Partial	Partial
10	Describes outcome measure and why this is applicable to type of analysis	Yes	Yes	Partial	Yes
11a	Fully describes design of study used and why this was sufficient (if single source used for effectiveness data)	N/A	Yes	Partial	N/A
11b	Fully describes search and synthesis methods (if multiple studies used for effectiveness data)	Yes	N/A	N/A	Partial
12	Describes population and methods used to determine preferences for outcomes (if applicable)	N/A	Yes	N/A	N/A
13a	Describes approach used to estimate resource use associated with alternative interventions, including primary and secondary research methods for valuing resource items by unit cost and calculating opportunity costs (if single study–based)	N/A	N/A	N/A	N/A
13b	Describes approach and data sources used to construct model health states, including primary and secondary methods for valuing resource items by unit cost and calculating pportunity costs (if model-based)	Yes	Yes	Yes	Yes
14	Reports dates of estimated resource quantities and unit costs. Describes methods for cost inflation and currency conversion	Yes	Yes	Yes	Yes
15	Describes and provides rationale for why specific model was chosen	Partial	Partial	Partial	Partial
16	Describes all assumptions underlying model, structural, and otherwise	Yes	Yes	Yes	Yes
17	Describes statistical and analytical methods used in evaluation	No	No	Yes	Yes
18	Reports values, ranges, references, and probability distributions for all parameters. Reports reason or source for probability distributions where uncertainty is present	Partial	N/A	Yes	Yes
19	Reports mean values for all main categories of estimated costs and outcomes, mean difference between competing options and incremental cost-effectiveness ratios	Yes	Yes	Yes	Yes
20a	Describes effect of sampling uncertainty on incremental cost, incremental cost-effectiveness ratio and effect of methodological assumptions (if single study–based)	N/A	N/A	N/A	N/A
20b	Describes effects of uncertainty for all input parameters, model structure, and assumptions (if model-based)	Yes	Yes	Yes	Yes
21	Reports differences in costs, outcomes, or cost-effectiveness that may be explained by variability between patient subgroups or other factors that cannot be improved with further information	Yes	Yes	Yes	Yes
22	Summarizes key findings and explains how they support conclusions. Discusses limitations, generalizability of findings, and applicability to the current body of knowledge	Yes	Yes	Yes	Yes
23	Discusses study funding and role (if applicable) of funding source in study conception, design, conduct, and reporting	Yes	Yes	Yes	Yes
24	Discusses potential conflicts of interest	Yes	Yes	Yes	Yes
	Total score (of applicable criteria)	19.5/23	19/23	19/23	19.5/23

N/A, not applicable to the study being evaluated.

1.135% (65-74 years), and 1.760% (≥75 years), above which UKA is not cost-effective compared to TKA. UKA demonstrates an age-dependent trend, consistently meeting cost-effective survivorship targets in patients aged 75 and older but progressively exceeding the recommended revision threshold at younger ages (Fig. 4). This has implications in both the policy and research arena.

Actual ARR reported by the Swedish, UK, NZ, and Australian registries (represented by the colored points in Fig. 4) range from 0.65% to 0.79% for patients aged ≥75. All values are below the calculated cost-effective ARR limit and IQR (represented by the box and whisker plot in Fig. 4). For patients aged 65-74, ARR reported by the above registries range from 1.01% to 1.33%. Three of 4 values lie within the calculated IQR for cost-effective implant survivorship. In patients aged <65, registry-reported ARR range from 1.62% to 2.13%, uniformly exceeding the calculated threshold of 1.471% for this age. Half of these registry values exceed the IQR. Our comparison of cost-effective ARR thresholds for UKA with published registry values suggests that UKA is currently not economically favorable in patients aged <65. Furthermore, the data indicate that cost-effectiveness as a function of implant survivorship is highest in patients aged ≥75. From a policy standpoint, this implies that cost-effective UKA utilization will be dependent on optimizing implant survivorship in younger patients. Below, we propose a series of initiatives by which this may be achieved, based on the recent literature.

Surgeon UKA caseload is a key modifiable determinant of failure following UKA, which may be leveraged to achieve the above target thresholds in both older and younger patients. UKA revision rates when performed by high-volume surgeons are 2.7- to 4.0-fold lower than those of low-volume surgeons [41-43]. This effect has been primarily attributed to less risk of technical error, as demonstrated by lower frequencies of aseptic loosening and malalignment among

Table 5
Age-Stratified Cost-Effective Threshold Annual Revision Rates of UKA vs TKA.

Age Category	Individual Cohorts			Combined Cohorts
	Study	Age at Index UKA	Cost-Effective Threshold (Annual % Revised)	Cost-Effective Threshold (Annual % Revised) Median (IQR)
<65 y	1[c]	45	1.358	1.471 (1.415-1.833)
	2[c]	55	1.471	
	3[d]	55	2.194	
65-74 y	4[c]	65	1.384	1.135 (1.011-1.260)
	5[b]	65	0.886	
≥75 y	6[c]	75	1.560	1.760 (1.660-2.880)
	7[a]	78	4.000	
	8[c]	85	1.760	

Median values in the “combined cohort” column are generated from the individual threshold values from each sample cohort within the corresponding age-group. Each individual data point was weighted equally, as economic decision models do not incorporate a discrete sample size.

UKA, unicompartmental knee arthroplasty; TKA, total knee arthroplasty; IQR interquartile range.

[a] Slover et al, 2006 [4].
[b] Soohoo et al, 2006 [3].
[c] Ghomrawi et al, 2015 [5].
[d] Konopka et al, 2015 [6].

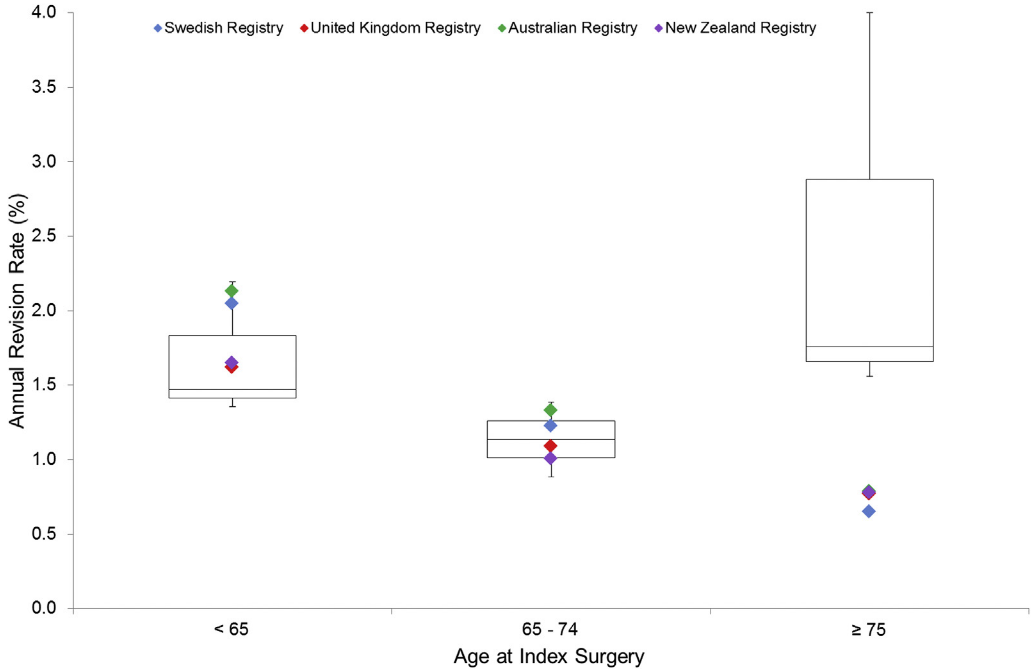

Fig. 4. Cost-effective threshold annual revision rates of UKA. This figure compares cost-effective threshold revision rates to actual revision rates. Box and whisker plots represent cost-effective threshold revision rates, above which UKA ceases to be cost-effective. The colored points show actual revision rate values derived from national registry data. Points within or below the corresponding interquartile range indicate that UKA is likely to be cost-effective. Taken together, the points show the general trend of current UKA survivorship against which to assess the cost-effectiveness of UKA.

revised patients [41,42]. Experienced UKA surgeons are also less likely to revise for potentially correctable or etiologies of pain, as illustrated by published failure modes [41]. Further research is ultimately required to distinguish between the effect of surgeon experience and possible confounding factors. As reported by Pabinger et al [14], revision rates reported by "designer" centers are typically lower than those published in registries by a factor of 7. High-volume UKA surgeons may be involved in the design of such implants, introducing an element of bias due to familiarity with technically demanding implants such as the Oxford III [42,44]. Surgeon preference is also likely to influence revision rates, with low-volume surgeons more likely to default to TKA in the presence of suboptimal outcomes. Finally, the effect of surgeon ownership of ambulatory facilities on the decision to revise has not been explored in depth.

The inverse correlation between surgeon UKA volume and revision rates is a well-documented phenomenon based on data from multiple registries [42,43]. Provided that this can be attributed to technical as opposed to confounding factors as enumerated above, a strong argument can be made for the implementation of a 2-track referral system based on procedural volume (Fig. 5). UKA should ideally be performed in high-volume centers, to maximize implant survivorship and cost-effectiveness vs TKA [43]. This is particularly important for patients at an inherently higher risk of implant failure (eg, aged <65 and/or borderline eligibility status). Under such a system, only patients with an inherently low failure risk (aged ≥75 and meeting all eligibility criteria) should be safely considered for low-volume hospitals as well. This may ultimately lead to the creation of regional UKA "hubs," particularly as cost-effectiveness comes to play a greater role in decision-making from both provider and payer perspectives [43,45]. The advantage afforded by a volume-based infrastructure may be further enhanced by the introduction of advanced technologies such as robotic assistance and computer navigation in high-volume centers. This (1) shifts resources to the patients most likely to benefit from precision alignment (eg, <65 years, as recommended above) and (2) ensures that capital-intensive technology is implemented in a cost-effective manner by restricting its use to a high-volume setting [46-49].

To complement the above policy measures, research should be concentrated toward the aim of improving UKA implant survivorship in young patients. This will entail age-stratified studies focusing on (1) risk analysis, (2) failure mode characterization, and (3) failure prevention (Fig. 5). Predictor studies are required to identify age-specific risk factors, following which associated failure modes may be elucidated and addressed through innovations in surgical technique. Cementless fixation, computer navigation, and robot-assisted platforms are of particular interest for younger patients, who may be at increased risk of mechanical failure (ie, aseptic loosening or tibial subsidence) due to higher levels of activity and functional demand [50-52].

This study is subject to several limitations. First, ARR values were obtained from CEA that used different model structures, assumptions, and inputs. However, this diversity of inputs ultimately contributes to the generalizability of the above findings and served as the main impetus for this meta-analysis. Second, it was necessary to mathematically derive the threshold ARR for the study by Soohoo et al, as the original model did not use a constant revision rate. However, the estimated base case and threshold ARR values were based on sources informing the model assumptions and the results of the sensitivity analysis. In the absence of the original model, this represents the best possible approximation. Third, it was neither feasible nor meaningful to perform significance testing between age-clustered threshold ARR calculations. The use of theoretical decision models by CEA studies effectively condenses the sample size to ($n = 1$), failing to reflect the statistical power of data based on national registries, payer databases, and systematic searches. While the results suggest a clinically meaningful difference between age-based threshold ARR values, the number of available studies at present is not sufficient to quantify the effect size. Fourth, each age cohort analyzed in the study by Ghomrawi et al was considered to be an individual data

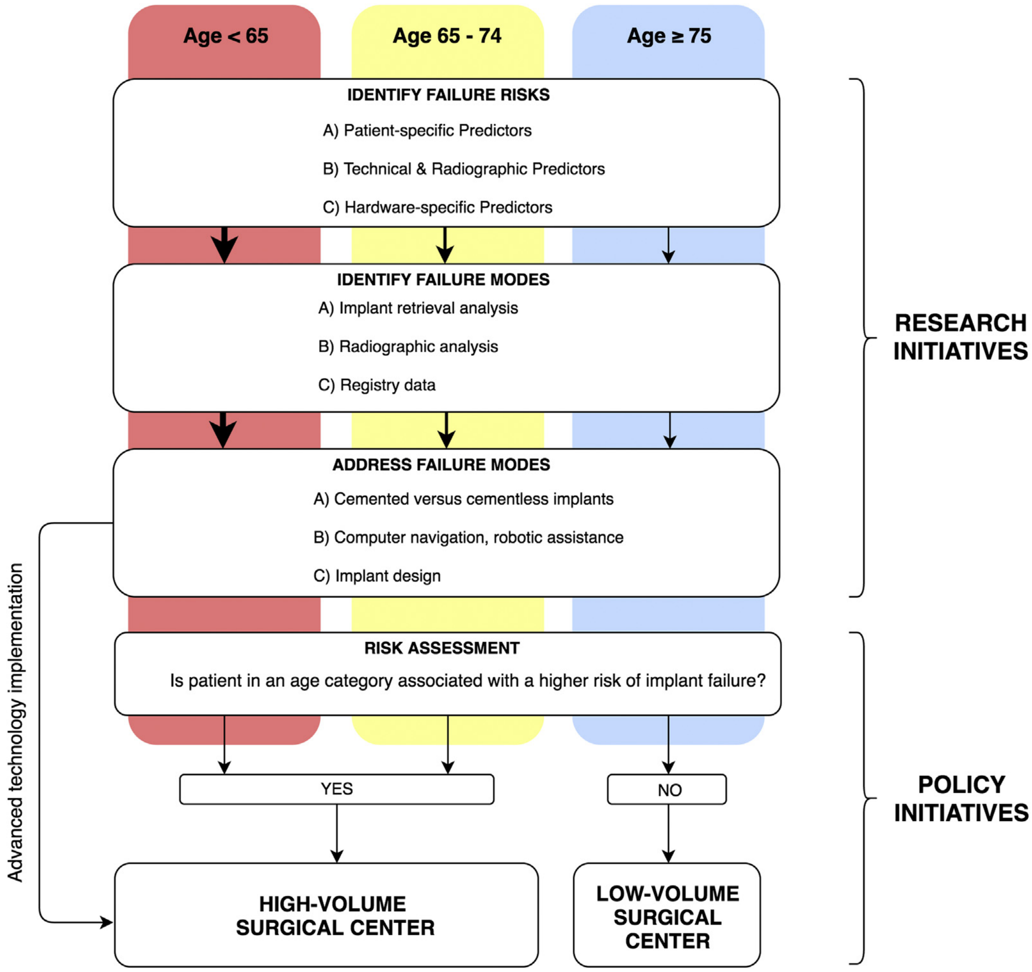

Fig. 5. Integrated research and clinical pathway to optimize UKA survivorship. This flowchart illustrates the research and policy-level recommendations to improve the survivorship of UKA, particularly in younger patients. Relative arrow sizes in the "Research" section denote priority for resource allocation, with larger arrows signifying a higher priority age category. While not reflected in this diagram, patients aged 75 or older who do not fulfill all eligibility criteria should also be diverted to high-volume surgery centers as a matter of priority, to minimize the risk of implant failure. Advanced surgical techniques (ie, robot-assisted platforms) should be preferentially adopted in high-volume facilities, to ensure cost-effective utilization of technology that requires significant up-front capital investment.

point. While this may skew the findings toward the assumptions of a single model, it was necessary to consider each cohort separately to generate target ARR by age category. Finally, cost-effectiveness was evaluated against a WTP of $50,000 per QALY. A $100,000 per QALY threshold may be preferable for CEA conducted from a societal perspective as proposed by Nwachukwu and Bozic [2]. However, it was not possible to modify the results of sensitivity analyses conducted by various authors to match this value. As TKA was the more expensive intervention in 7 of 8 cohorts, adoption of a $100,000 per QALY WTP would decrease the threshold (eg, requiring lower revision rates) for UKA to achieve/maintain cost-effectiveness. Despite these limitations, the present study serves as the best available effort to consolidate the existing literature to reach clinically relevant conclusions. Future studies will be required to validate these preliminary findings and recommendations.

Conclusion

The findings imply that implant survivorship is currently a limiting factor toward cost-effective UKA utilization in patients aged <65. Furthermore, cost-effectiveness as a function of implant survivorship is highest in patients aged ≥75. Preferential use of high-volume surgical centers may render this procedure cost-effective in younger patients. Alternatively, the already-favorable ARR of UKA in older patients may permit the use of low-volume facilities while still achieving lower costs and greater effectiveness vs TKA. Our findings represent an opportunity for resource reallocation within health systems to permit cost-effective utilization of UKA across a broader population segment. To our knowledge, this represents the first framework for meta-analysis of CEA studies to derive actionable implant performance targets.

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Appendix

The following calculation and conversion was performed for 5 age cohorts (45, 55, 65, 75, and 85 years of age). One-way deterministic sensitivity analysis was performed to identify the threshold annual failure probabilities below which UKA is cost-effective. This was determined by varying age and time-dependent UKA failure probabilities by 0.1% increments against a WTP threshold of $50,000 per QALY. Having identified the cost-effective upper limit of annual failure probabilities, a 10,000 patient simulation was run. A stage table was generated and exported to a spreadsheet (Excel 2008, Microsoft Inc, Redmond, WA), specifying the status of each theoretical patient at the end of each simulation year (terminating at age 100). Patients were classified under 1 of 3 categories following each cycle: (A) component in situ, consisting of the "full benefit," "limited benefit," and "failed declining revision" states, (B) dead, and (C) undergo revision TKA. A scatter plot of years following surgery (x-axis) vs components in situ (y-axis) was generated, comprising a survivorship curve (Fig. 3A). Observed component-years were approximated as the area under the survivorship curve. This was estimated by integrating the curve as a midpoint Riemann sum (to account for dropout due to death or revision within a given year; Fig. 3B). The total number of revisions per cohort was divided by the observed component-years to estimate the ARR in percentage revised per observed component-year.