Templating in shoulder arthroplasty – A comparison of 2D CT to 3D CT planning software: A systematic review

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Abstract

Background: Computed tomography (CT) utilizing computer software technology to generate three-dimensional (3D) rendering of the glenoid has become the preferred method for preoperative planning. It remains largely unknown what benefits this software may have to the intraoperative placement of the components and patient outcomes.

Purpose: The purpose of this systematic review is to compare 2D CT to 3D CT planning in total shoulder arthroplasty.

Study design: Systematic review.

Methods: A systematic database search was conducted for relevant studies evaluating the role of 3D CT planning in total shoulder arthroplasty. The primary outcome was component placement variability, and the secondary outcomes were intra- and inter-observer reliability in the context of preoperative planning.

Results: Following title-abstract and full-text screening, six eligible studies were included in the review ($n = 237$). The variability in glenoid measurements between 3D CT and 2D CT planning ranged from no significant difference to a 5° difference in version and 1.7° difference in inclination ($p < 0.05$). Posterior bone loss was underestimated in 52% of the 2D measured patients relative to 3D CT groups. Irrespective of 2D and 3D planning (39% and 43% of cases respectively), surgeons elected to implant larger components than those templated. There was no literature identified comparing differences in time, cost, functional outcomes, complications, or patient satisfaction.

Conclusion: The paucity of evidence exploring clinical parameters makes it difficult to comment on clinical outcomes using different methods of templating. More studies are required to identify how improved radiographic outcomes translate into improvements that are clinically meaningful to patients.

Keywords

computed tomography, glenoid, TSA

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Introduction

Shoulder arthroplasty is widely utilized for the management of various shoulder pathologies. Anatomic total shoulder arthroplasty (TSA) is the definitive treatment of primary glenohumeral osteoarthritis, while reverse TSA (rTSA) plays an essential role in the management of rotator cuff arthropathy, irreparable massive rotator cuff tears, complex proximal humerus fractures, prosthetic revisions, and severe bone erosion.^{1–3} Despite advancements in shoulder arthroplasty, loosening and failure of the glenoid component continue to be the

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primary reasons for aseptic mid- and long-term complications and revisions.² Gonzalez et al. report 24% of anatomic TSA complications may result from failure of the glenoid component and Jain et al. report 21% of reverse total shoulder procedures are indirectly related to glenoid component malpositioning.^{4,5} An improperly positioned glenoid is potentially at risk for loosening due to destabilizing forces such as notching, bony impingement, inadequate fixation, or increased eccentric loading.² Accurate positioning of the glenoid component as well as humeral components are essential for the longevity of the components.

Computed tomography (CT) facilitates detailed two-dimensional (2D) or three-dimensional (3D) understanding of the glenohumeral joint. Due to advancements in computer software, pre-operative planning can be performed utilizing CT data allowing for detailed preoperative planning with virtual components. With the rapid advancement of these 3D planning technologies, it is essential to understand and identify their reported benefits. Although there is the potential for this software to improve the accuracy of glenoid component implantation, especially in patients with severe glenoid pathology, it is unknown whether this is truly the case. The primary outcome of this study was to evaluate the clinical utility of 3D templating in shoulder arthroplasty by evaluating component implantation accuracy. The secondary outcomes were intra- and inter-observer reliability in the context of preoperative planning.

Methods

This systematic review was conducted and reported following the methods of the *Cochrane Handbook for Systematic Reviews of Interventions* and the PRISMA guidelines.⁶ The protocol was validated and registered to PROSPERO (CRD42018116086).

Search strategy

A comprehensive search of six different databases: PubMed, MEDLINE via OVID, EMBASE via OVID, EBSCO (via EBSCOHost), The Cochrane Central Register of Controlled Trials (CENTRAL), and the US National Institutes for Health clinical trials registry (www.ClinicalTrials.gov)) from the earliest records published to 5 April 2019. We used MESH headings and subheadings in various combinations, supplemented with free text to increase sensitivity. Keywords related to shoulder arthroplasty such as “arthroplasty” and “shoulder” were combined with the search terms “three-dimensional” and “preoperative planning.” A comprehensive and sensitive search strategy was adapted from the Cochrane Database of

Systematic Reviews¹ (Supplementary Table 1). A search strategy was developed for each unique database. Additionally, the citations of relevant studies were reviewed for additional relevant articles that met the inclusion criteria.

Eligibility

Studies included in this systematic review met the following inclusion criteria: (1) patients undergoing shoulder arthroplasty using 3D planning, (2) randomized, non-randomized, quasi-randomized, and observational clinical studies, and (3) studies with patients (adult and children) undergoing different variations of shoulder arthroplasty were included, such as anatomic and reverse arthroplasty. There were no date or language limitations placed on the search. Studies were excluded if they were: (1) cadaveric studies, (2) animal studies, or (3) patient specific instrumentation studies. Comments, letters, editorials, protocols, guidelines, and systematic reviews were also excluded from this study.

Outcomes

The primary outcome is component placement variability between 3D CT and 2D CT templating. Secondary outcomes include reproducibility, reliability, and influence on decision making.

Data extraction

Two reviewers (ORO and IN) independently screened articles by title and abstract for eligibility and full text review of all potentially eligible studies was performed. Any disagreements that could not be resolved by discussion were resolved by consensus with a blinded third reviewer (NH). Data extraction was completed independently by each reviewer on a standardized Excel spreadsheet. Extracted data included the characteristics of the study (e.g., demographic characteristics, funding sources, number of shoulders, and gender), study design, type of planning software, study objectives, follow-up period, and data related to clinical and radiologic outcomes.

The quality and risk of bias assessment of the included studies was performed in duplicate (ORO and IN). Quality of non-randomized studies was evaluated using the Methodological Index for non-randomized studies (MINORS) score. MINORS score uses a global score of 24 in comparative studies and 16 for non-comparative studies, evaluating 8 or 12 domains of bias. Methodological quality was categorized a priori as: very low-quality evidence (score 0–6); low quality of evidence (score 7–10); fair quality (score 11–15); and high quality (score >16) evidence for

non-randomized studies.⁷ The Cochrane Risk of Bias tool was used to evaluate included randomized trials. The Cochrane Risk of Bias tool evaluates articles in six to seven domains as either: unclear, high, or low risk of bias.⁸ Overall study risk of bias and methodological quality assessment was used to inform the validity of the recommendations regarding the use of 3D computer planning. Sources of funding and potential conflicts of interest were also described.

Statistical analysis

Inter-observer agreement for assessments of eligibility was calculated with the Cohen κ (kappa) statistic. Agreement coefficients were categorized a priori as almost perfect agreement ($\kappa = 0.81$ – 1.00), substantial agreement ($\kappa = 0.61$ – 0.8), moderate agreement ($\kappa = 0.41$ – 0.6), and fair agreement ($\kappa = 0.21$ – 0.40).⁹ For any calculations, an error of measurements such as standard deviations and confidence intervals (CI) are presented where applicable.

Results

Study selection

The search resulted in a total of 1139 articles. After application of inclusion and exclusion criteria 35 full-text articles underwent full text review of which six were included for qualitative synthesis (Figure 1). The agreement between reviewers regarding study eligibility was substantial ($\kappa = 0.804$ (95% CI 0.596–1.00)).

Study characteristics

The included studies were conducted between 2008 and 2018. The majority of the studies (4/6 studies) were published within the past three years (Table 1). The search resulted in one paper with level 1 evidence ($n = 46$), four papers with level 2 evidence ($n = 107$), and two papers with level 3 evidence ($n = 84$). Of the six eligible studies, four were performed in the United States, one in France, and one in Germany ($n = 35$).

Figure 1. Flowchart of results.

Table 1. Studies included in the systematic review.

Study	Country	Year	Study design (level of evidence)	Sample size	Age	Gender (% of males)	Preoperative glenoid morphology	Minors score
Observational trials								
Boileau et al. ¹¹	France	2018	3	60	66	NR	Walch classification: <ul style="list-style-type: none"> • Type A1 = 17 • Type A2 = 16 • Type B1 = 8 • Type B2 = 9 • Type C = 10 	22
Hoenecke et al. ¹²	USA	2010	2	33	75	33.3%	NR	18
Saifi et al. ¹³	USA	2017	3	24	70.3	62.5%	NR	20
Scalise et al. ¹⁵	USA	2008	2	24	62	39%	NR	23
Werner et al. ¹⁷	Germany	2017	2	50	67.8	NR	Walch classification: <ul style="list-style-type: none"> • Type A1 = 14 • Type A2 = 10 • Type B1 = 3 • Type B2 = 14 • Type C = 1 	22
Randomized controlled trials								
Iannotti et al. ¹⁶	USA	2015	1	46	46	NR	Walch classification: <ul style="list-style-type: none"> • Type A1 = 14 • Type A2 = 10 • Type B1 = 3 • Type B2 = 14 • Type C = 1 	High risk of bias

A total of 237 imaged shoulders were included in this review. The mean age of the included participant was 65 years old (range 46 to 75) and the mean total sample size of the included studies was 39.5 patients (range 24–60).

All six included studies compared 3D CT preoperative computer planning to 2D CT planning. Glenoid implantation accuracy was assessed in one study¹⁶ and was measured by calculating the mean error from the planned central point position. All of the included patients were undergoing pre-operative evaluation for TSA. None of the clinical studies identified evaluated the role of 3D imaging on glenoid implantation in rTSA.

Two variations of pre-operative planning systems were commonly reported in the literature: automated and manual/semi-automated planning. Four studies^{11–14} reported on automatic planning software which generates automatic reconstructions and calculated measurements (n = 167) (Table 2). Two studies^{15,16} used manual systems which involve manual planning

assistance from a technician (n = 70). The planning software utilized included Glenosys Software (two studies), Mimics software (two studies), OrthoVis (one study), and SOMATOM (one study) (Table 2).

Study quality and risk of bias within studies

The mean MINORS score was 21.5 (± 1.79) which suggests the included observational studies were of high methodological quality. However, most frequently, studies lacked prospective calculation of the study size (Supplementary Table 2). The randomized controlled trial¹⁶ by Iannotti et al. demonstrated a high risk of bias. In reference to the Cochrane Risk of Bias tool, this study was at high risk for selective outcome reporting, incomplete outcome data, and other biases. This was demonstrated by reported outcomes which were not listed in the methods which may not have been established a priori. Study details were sought on the U.S. Clinical trial registry but have since been redacted (ClinicalTrials.gov, NCT01801241). Other biases

Table 2. Summary of the data provided by each study regarding measured outcomes.

Study	Planning software	Type of replacement (aTSA or rTSA)	Automated/manual	Experimental group	Control group	Outcomes: Results
Observational studies						
Boileau et al. ¹¹	Glenosys software (Glenosys 1.3; Imascap, Brest, France)	NA	Automated software	3D CT	2D CT	<p>Glenoid measurement:</p> <ul style="list-style-type: none"> Glenoid version measured with the Glenosys method (3D) did not differ significantly from that measured with any of the four manual methods. Glenoid inclination measured with the Glenosys method did not differ significantly from that measured with the Maurer method. The difference between the overall average 2D and 3D measurements was not significant ($p = 0.45$). <p>Inter-observer and intra-observer reliability</p> <p>The mean difference in the Glenosys glenoid version measurement was:</p> <ul style="list-style-type: none"> 2.0 ± 4.5 (CCC = 0.93) Friedman method 2.5 ± 3.2 (CCC = 0.95) compared with the corrected Friedman method 1.5 ± 4.5 (CCC = 0.94) compared with the Ganapathi-Iannotti method 1.8 ± 3.8 (CCC = 0.95) compared with the Lewis-Armstrong method
Hoenecke et al. ¹²	Materialise Interactive Medical Image Control System (Mimics) software	NA	Automated software	3D CT	2D CT	<p>Glenoid measurement:</p> <ul style="list-style-type: none"> True version using 3D CT reconstruction was mean -8.6° ($\pm 9.8^\circ$). The average absolute error in the version measured on the 2D CT slice passing through the tip of the coracoid was 5.1° (range, 0°–16°; $p < 0.001$). <p>Glenoid wear:</p> <p>On high-resolution 3D CT reconstructions, the location of maximum wear was most commonly posterior and was missed on the clinical 2D CT slices in 52% of cases.</p>

(continued)

Table 2. Continued

Study	Planning software	Type of replacement (aTSA or rTSA)	Automated/manual	Experimental group	Control group	Outcomes: Results
Saifi et al. ¹³	Materialise Interactive Medical Image Control System (Mimics) software	TSA	Automated software	3D CT	3D CT limited to 2D rotation	<p>Intra- and inter-observer templating reliability</p> <p>Intra-observer agreement</p> <ul style="list-style-type: none">Overall intra-observer agreement was substantial (0.67) in 2D rotation ($p < 0.001$) and moderate (0.58) in 3D rotation ($p < 0.001$). <p>Inter-observer agreement</p> <ul style="list-style-type: none">In 2D rotation, overall inter-observer agreement was fair (0.36) for trial 1 ($p < 0.001$) and fair (0.32) for trial 2 ($p < 0.001$).In 3D rotation, overall inter-observer agreement was moderate (0.54) for trial 1 and moderate (0.43) for trial 2 ($p < 0.001$). <p>In both 2D and 3D groups, surgeons tended to template glenoid components smaller than those implanted intraoperatively, especially in female patients:</p> <ul style="list-style-type: none">2D modelling: 32% of patients had a smaller component based on templating and 7% had larger components.3D modelling: 27% of patients had a smaller component selected based on templating and 16% had larger component selected intraoperatively.

(continued)

Table 2. Continued

Study	Planning software	Type of replacement (a TSA or rTSA)	Automated/manual	Experimental group	Control group	Outcomes: Results
Scalise et al. ¹⁵	SOMATOM Sensation 64 (Siemens Medical Solutions USA, Malvern, Pennsylvania)	TSA	Manual software	3D CT	2D CT	<p>Glenoid measurement:</p> <ul style="list-style-type: none"> The average glenoid version measured $-17^{\circ} \pm 2.2$ on the 2D imaging and $-19^{\circ} \pm 2.4$ on the 3D imaging ($p < 0.05$). Inter-rater agreement was very high for the measurement of glenoid version on 2D and 3D studies (coefficient=0.95 and 0.96, respectively). <p>Magnitude of bone loss:</p> <ul style="list-style-type: none"> The average posterior glenoid bone loss measured 9 ± 2.3 mm on the 2D imaging and 7 ± 2 mm on 3D images ($p < 0.05$). The average anterior bone loss measured 1 mm on both the 2D and the 3D images. The intraclass correlation coefficients for anterior bone loss increased significantly with use of the 3D data (from 0.36 to 0.70; $p < 0.05$). Observers were more likely to locate mid-anterior glenoid bone loss on the basis of the 3D data ($p < 0.05$). <p>Glenoid prosthesis implant fit (judgment):</p> <ul style="list-style-type: none"> Inter-observer kappa agreement: 2D planning: 0.67 (substantial); 3D: 0.87 (almost perfect agreement). <p>Preoperative surgical planning:</p> <ul style="list-style-type: none"> Inter-observer kappa agreement: 2D: 0.29 (fair agreement); 3D: 0.49 (moderate agreement). In cases in which the decisions based on 2D and 3D data differed, the most frequent change (17/37 cases) was from "accept a reamed position other than the physiologic version" on the 2D images to "ream to physiologic glenoid version" on the 3D images.

(continued)

Table 2. Continued

Study	Planning software	Type of replacement (aTSA or rTSA)	Automated/manual	Experimental group	Control group	Outcomes: Results
Werner et al. ¹⁷	Glenosys software (Glenosys 1.3; Imascap, Brest, France)	TSA	Automated software	3D CT	2D CT	<p>Glenoid measurement:</p> <p>Mean deviation in 2D measurements compared with 3D values:</p> <ul style="list-style-type: none"> Inclination: -1.7° (range, -26 to 20°; standard deviation, 8.4) for glenoid inclination. Version: -3.1° (range, -30° to 20°; standard deviation, 7.0) ($p=0.003$). The difference for glenoid inclination was not statistically significant ($p=0.18$). <p>Preoperative surgical planning:</p> <ul style="list-style-type: none"> The 2D CT measurements resulted in agreement on the choice of implant in 45 patients. In the remaining five patients, the definitive implant was changed from anatomic to reverse arthroplasty in two patients and from reverse to anatomic prosthesis in three patients after 3D CT planning. In two of the patients that all three observers had agreed on, 3D planning resulted in a change of the desired implant, moving from anatomic to reverse shoulder arthroplasty.
Randomized controlled trials						
Iannotti et al. ¹⁶	OrthoVis, Custom Orthopaedic Solutions	TSA	Manual. Engineer planned; surgeon reviewed	3D CT	2D CT and PSI	<p>Glenoid implant position:</p> <ul style="list-style-type: none"> There was an increased 7° deviation of planned inclination ($p<0.001$) of the glenoid implant position in the 2D imaging group when compared with the 3D group. There was no other significant difference in all other implant measures.

PGM: preoperative glenoid morphology; PSG: patient-specific guide.

include unexplained and uneven treatment groups. Notably, 3/6 studies had one or more authors who had a financial relationship to software imaging companies which could be perceived to influence the written work, these conflicts of interest increase the potential risk of bias (Supplementary Table 3).

Outcome results

Glenoid measurement accuracy. Four studies^{11,12,15,17} including 167 patients compared the measurement accuracy of 3D planning to 2D CT, measuring the glenoid version and inclination of arthritic shoulders. Three studies^{12,15,17} found a significant statistical difference between the measurements of the two imaging modalities.

Scalise et al.¹⁵ and Werner et al.¹⁷ measured the glenoid of patients exclusively undergoing anatomic TSA while Hoenecke et al.¹² and Boileau et al.¹¹ did not report the type of TSA. In the anatomic TSA studies, Scalise et al.¹⁵ reported a 2° difference of measured preoperative glenoid version between 2D and 3D measurements ($n = 24$, $p < 0.05$). Werner et al.¹⁷ reported a mean difference of 3.1° for preoperative glenoid version and 1.7° for inclination assuming 3D CT as the gold standard ($n = 50$, $p = 0.003$). Hoenecke et al.¹² reported a mean measurement difference of 5.1° version between 2D CT and 3D planning ($n = 33$, $p < 0.001$). Boileau et al.¹¹ found no significant difference between the 3D CT and three different types of 2D CT measurement techniques ($p = 0.45$). The same study also revealed no significant difference in measurement of glenoid version and inclination between automated 3D preoperative planning and manual or semi-automated planning software.

Observer identification of glenoid wear. Hoenecke et al.¹² and Scalise et al.¹⁵ evaluated the influence of imaging modality on an observer's ability to interpret glenoid wear on preoperative imaging. Hoenecke et al.¹² ($n = 33$) reported 2D reconstruction resulted in an observer missing or underappreciating posterior glenoid wear in 52% of cases which were acknowledged when 3D CT imaging was used for pre-operative evaluation. Scalise et al.¹⁵ further demonstrated observers were more likely to locate mid-anterior glenoid bone loss from the 3D data ($p < 0.05$). The same study¹⁵ also found a statistically significant difference (2 mm, $p < 0.05$) in measurement magnitude of posterior glenoid bone loss when 3D reconstructive models were utilized in comparison to 2D.

Reliability of measurements. The reliability of 3D CT preoperative planning technology was compared to 2D CT by Saifi et al. and Boileau et al. Each study assessed

reliability in a unique capacity. Boileau et al.¹¹ assessed glenoid measurement reliability while Saifi et al.¹³ assessed correlation in component templating in anatomic TSA patients. Boileau et al.¹¹ reported that measurements of 3D automated software had an excellent correlation to manual or semi-automated 2D and 3D methods ($p < 0.05$). Saifi et al.¹³ assessed intra- and inter-observer templating reliability in total shoulder arthroplasty. Two-dimensional imaging demonstrated a greater intra-observer agreement ($p < 0.001$), but 3D imaging had greater inter-observer agreement ($p < 0.001$).¹³

Surgical decision making. Three studies,^{15,13,17} all of which included TSA patients exclusively, compared decision making between 3D CT and 2D CT. Scalise et al.¹⁵ suggested preoperative surgical decisions changed in 37/96 cases when exposed to 3D imaging after 2D imaging. They also reported improved inter-observer agreement in glenoid implant selection ($p = 0.006$). Werner et al.¹⁷ proposed 2D planning produced the same choice of implant in 45/50 patients among three different observers. In the remaining five patients, observers revised their decision and changed the implant when shown the 3D virtual image. In the same study, despite all independently agreeing upon the management of two patients all three observers independently revised their surgical approach after 3D CT review. Saifi et al.¹³ demonstrated that in both 2D and 3D templating, "when templates and implants differed" (39% and 43% of cases, respectively), surgeons were more likely to template components smaller than those used intraoperatively.

Glenoid positioning. In an RCT, Iannotti et al.¹⁶ evaluated the accuracy of glenoid implantation using 3D pre-operative planning compared to 2D CT and 3D patient specific instrumentation treatment arms. The comparison of 3D CT to 2D pre-operative imaging resulted in an estimated 7° deviation from the planned inclination of the planned glenoid implant position ($p < 0.001$). There were no other significant differences in all other implant measures including: version, antero-posterior, and superoinferior position. According to our search, the efficacy of 3D CT planning in precise glenoid implantation in rTSA has yet been investigated in clinical studies.

Discussion

A key finding in this systematic review was that although there were potentially small differences between 3D planning and 2D CT, these differences were quite small and at times, unlikely to be clinically significant with limited reliability. Studies do not

support the notion that 3D CT is advantageous over 2D templating despite industry support for 3D computer planning. Based on the current literature, it is likely that patients will benefit from any CT evaluation and it is unclear if there is any clinical advantage to 3D templating.

The literature included in this review support that 3D planning enables an improved anatomical assessment of glenoid bone loss pre-operatively. The majority of included studies concluded that 3D planning technology results in different radiographic measurements when compared to standard 2D planning. Given a lack of gold standard, it cannot be ascertained that such differences represent improved evaluation. No study assessed cost, operative time, blood loss, infection rates, revision rates or other complications in shoulder arthroplasty. Unfortunately, none of the available literature has proven clinically how this pre-operative information is beneficial for patients. According to our search criteria, the evidence is quite limited for in-vivo studies assessing the clinical utility of 3D CT pre-operative planning. That being said, the rapid evolution of this technology to incorporate associated patient-specific instrumentation may significantly transform the utility of this technology to reliably guide improved component position in severe glenoid deformity.

A recent review proposed that computer-assisted trauma surgery was correlated with increased surgical time, requirements for unique set up, and costs while offering no clinical advantage in trauma cases compared with traditional methods.²⁰ Similarly, despite evidence suggesting computer-assistance and PSI improves alignment in total knee arthroplasty (TKA), systematic reviews revealed that neither PSI or computer-assisted TKA demonstrated cost-effectiveness or improved surgical efficiency.^{21–23} Sassoon et al.²² highlighted, there was no evidence to support the improvement of pain, activity, function, or ROM when knee PSI was compared with conventional instrumentation. Burnett et al.²³ suggest that while navigated TKA improves coronal alignment there was limited evidence to suggest improvements in any other variable and was associated with its own unique complications. Analogous to the other technological advancements in different orthopedic subspecialties, 3D CT planning in shoulder arthroplasty may demonstrate small radiographic differences which may not prove to be clinically useful. Nonetheless, the application of 3D technology in the context of orthopedic surgery is relatively new and future trials investigating long-term outcomes such as survivorship will better delineate the efficacy of these tools.

Future research should consider the impact of 3D planning on operational efficiency and surgeon experience as well as cost-analysis of this technology.

Plausibly, the surgeon's experience may play a role in the usefulness of 3D CT planning technology. An experienced orthopedic surgeon is likely to be well-founded and can handle unanticipated change in the operative suite. However, a trainee or more junior surgeon would likely benefit from having all available information before entering the operative suite. Additionally, the influence of this technology on total preoperative and operative time warrants investigation. 3D CT planning introduces an additional step of 3D rendering and virtual glenoid component trial but may ultimately translate into decreased costs associated with sterilizing ill-fitting components and operative times. While 3D CT planning may not be impressively useful for the standard, uncomplicated TSA, it could be more valuable in cases with severe bone loss, in patients with complex anatomy or in the revision setting. Such benefit has been highlighted in complex knee deformities and revisions and may be similarly more impactful in modified Walch B2/3 and C glenoid morphology.²⁴ Notably, some studies in this review were conducted before the widespread use of augmented glenoid components. Three-dimensional planning may more readily influence surgical decision making in the context of selecting augmented glenoid components in efforts to minimize rates of peg perforation, retroversion, and restoring natural glenohumeral anatomy.²⁵

Early cost-effectiveness analysis with the consideration of the many different stakeholders should be performed. If the cost of 3D-rendered imaging is only marginally more expensive than 2D CT, the threshold for clinical superiority may be lowered as there has been reported radiographic benefit and no reported risks. However, if the technology is significantly more expensive, it should prove clear clinical superiority before application. Most importantly future research needs to address patient-reported outcomes, complication rates, and survivorship rates of shoulder prosthesis implanted using 3D planning technology versus the conventional method. While biomechanical and cadaveric studies have demonstrated the potential of this technology, in-vivo studies have not proven a clinically important difference to patients.^{26,27}

The strengths of this systematic review include the use of a pre-specified registered protocol, sensitive search strategy and adherence to the PRISMA recommendations. The limitations of this review include: the small number of studies included, lack of rTSA studies, inclusion of predominantly observational studies, and the number of patients included in individual studies. Furthermore, the studies included in this review only reported surrogate outcomes for glenoid survivorship such as angles of retroversion and inclination in pre-operative glenoid analysis. None of the included studies

formally assessed rates of glenoid loosening or patient-reported outcomes. A number of the studies included in this review had authors with a financial relationship with the 3D software companies, which increases the risk of bias in favor of the sponsor's products (Supplementary Table 3). It is difficult at this point to ascertain whether the lack of reported clinical outcomes is a result of publication bias or lack of clinical investigation.

Conclusion

The studies included in this review suggest the main benefits of 3D planning compared to 2D CT planning were improved preoperative foresight of the glenohumeral joint and glenoid implantation accuracy. There is inconsistent evidence to suggest improvement in other outcome measures, and there is no published evidence regarding patient-reported outcomes or prosthetic glenoid longevity. Published clinical research has been conducted exclusively in anatomic TSA and the value of 3D CT technology in rTSA cannot be fully established in this review. The evidence-base of this review has methodological limitations, most notably the lack of randomized controlled trials and small sample sizes. Further research is recommended to determine the clinical benefit of 3D planning for shoulder replacements.

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Supplemental Material

Supplemental material for this article is available online.

References

1. Singh JA, Sperling J, Buchbinder R, et al. Surgery for shoulder osteoarthritis. *Cochrane Database Syst Rev* 2010; CD008089.
2. Strauss EJ, Roche C, Flurin P-H, et al. The glenoid in shoulder arthroplasty. *J Shoulder Elbow Surg* 2009; 18: 819–833.
3. Barco R, Savvidou OD, Sperling JW, et al. Complications in reverse shoulder arthroplasty. *EFORT Open Rev* 2016; 1: 72–80.
4. Gonzalez J-F, Alami GB, Baque F, et al. Complications of unconstrained shoulder prostheses. *J Shoulder Elbow Surg* 2011; 20: 666–682.
5. Jain NB and Yamaguchi K. The contribution of reverse shoulder arthroplasty to utilization of primary shoulder arthroplasty. *J Shoulder Elbow Surg* 2014; 23: 1905–1912.
6. Higgins J and Green S. *Cochrane Handbook for Systematic Reviews of Interventions*, Version 5.1.0 (updated March 2011). *Cochrane Collab* 2011, <http://handbook.cochrane.org> (accessed 8 November 2019).
7. Slim K, Nini E, Forestier D, et al. Methodological index for non-randomized studies (minors): development and validation of a new instrument. *ANZ J Surg* 2003; 73: 712–716.
8. Higgins JPT, Altman DG, Gøtzsche PC, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *Brit Med J* 2011; 343: d5928.
9. Landis JR and Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977; 33: 159.
10. Jacquot A, Gauci M-O, Chaoui J, et al. Proper benefit of a three dimensional pre-operative planning software for glenoid component positioning in total shoulder arthroplasty. *Int Orthop* 2018; 42: 2897–2906.
11. Boileau P, Cheval D, Gauci M-O, et al. Automated three-dimensional measurement of glenoid version and inclination in arthritic shoulders. *J Bone Joint Surg Am* 2018; 100: 57–65.
12. Hoenecke HR, Hermida JC, Flores-Hernandez C, et al. Accuracy of CT-based measurements of glenoid version for total shoulder arthroplasty. *J Shoulder Elbow Surg* 2010; 19: 166–171.
13. Saifi C, Noticewala MN, Greiwe RM, et al. Reliability of 3-dimensional glenoid component templating and correlation to intraoperative component selection. *Am J Orthop (Belle Mead NJ)* 2017; 46: E280–92.
14. Favre P, Seebeck J, Thistlethwaite PAE, et al. In vitro initial stability of a stemless humeral implant. *Clin Biomech* 2016; 32: 113–117.
15. Scalise JJ, Codsí MJ, Bryan J, et al. The influence of three-dimensional computed tomography images of the shoulder in preoperative planning for total shoulder arthroplasty. *J Bone Joint Surgery Am* 2008; 90: 2438–2445.
16. Iannotti JP, Weiner S, Rodriguez E, et al. Three-dimensional imaging and templating improve glenoid implant positioning. *J Bone Joint Surg Am* 2015; 97: 651–658.
17. Werner BS, Hudek R, Burkhart KJ, et al. The influence of three-dimensional planning on decision-making in total shoulder arthroplasty. *J Shoulder Elbow Surg* 2017; 26: 1477–1483.
18. Atesok K and Schemitsch EH. Computer-assisted trauma surgery. *J Am Acad Orthop Surg* 2010; 18: 247–258.
19. Anderl W, Pauzenberger L, Kölblinger R, et al. Patient-specific instrumentation improved mechanical alignment, while early clinical outcome was comparable to conventional instrumentation in TKA. *Knee Surg, Sport Traumatol Arthrosc* 2016; 24: 102–111.

20. Sassoon A, Nam D, Nunley R, et al. Systematic review of patient-specific instrumentation in total knee arthroplasty: new but not improved. *Clin Orthop Relat Res* 2015; 473: 151–158.
21. Burnett RSJ and Barrack RL. Computer-assisted total knee arthroplasty is currently of no proven clinical benefit: a systematic review. *Clin Orthop Relat Res* 2013; 471: 264–276.
22. Venkatesan M, Mahadevan D and Ashford R. Computer-assisted navigation in knee arthroplasty: a critical appraisal. *J Knee Surg* 2013; 26: 357–362.
23. Sabesan V, Callanan M and Sharma V. Guidelines for the selection of optimal glenoid augment size for moderate to severe glenohumeral osteoarthritis. *J Shoulder Elbow Surg* 2014; 23: 974–981.
24. Iannotti J, Baker J, Rodriguez E, et al. Three-dimensional preoperative planning software and a novel information transfer technology improve glenoid component positioning. *J Bone Joint Surg Am* 2014; 96: e71.
25. Hoenecke HRJ, Hermida JC, Dembitsky N, et al. Optimizing glenoid component position using three-dimensional computed tomography reconstruction. *J Shoulder Elbow Surg* 2008; 17: 637–641.