Transcatheter aortic valve implantation versus surgical aortic valve replacement in patients with severe aortic stenosis: a systematic review and meta-analysis

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ABSTRACT

Objectives Patients undergoing surgery for severe aortic stenosis (SAS) can be treated with either transcatheter aortic valve implantation (TAVI) or surgical aortic valve replacement (SAVR). The choice of procedure depends on several factors, including the clinical judgement of the heart team and patient preferences, which are captured by actively informing and involving patients in a process of shared decision making (SDM). We synthesised the most up-to-date and accessible evidence on the benefits and risks that may be associated with TAVI versus SAVR to support SDM in this highly personalised decision-making process.

Design Systematic review and meta-analysis.

Data sources MEDLINE (Ovid), Embase (Ovid) and the Cochrane Central Register of Controlled Trials (CENTRAL; Wiley) were searched from January 2000 to August 2020 with no language restrictions. Reference lists of included studies were searched to identify additional studies.

Eligibility criteria Randomised controlled trials (RCTs) that compared TAVI versus SAVR in patients with SAS and reported on all-cause or cardiovascular mortality, length of stay in intensive care unit or hospital, valve durability, rehospitalisation/reintervention, stroke (any stroke or major disabling stroke), myocardial infarction, major vascular complications, major bleeding, permanent pacemaker (PPM) implantation, new-onset or worsening atrial fibrillation (NOW-AF), endocarditis, acute kidney injury (AKI), recovery time or pain were included.

Data extraction and synthesis Two independent reviewers were involved in data extraction and risk of bias (ROB) assessment using the Cochrane tool (one reviewer extracted/assessed the data, and the second reviewer checked it). Dichotomous data were pooled using the Mantel-Haenszel method with random-effects to generate a risk ratio (RR) with 95% CI. Continuous data were pooled using the inverse-variance method with random-effects and expressed as a mean difference (MD) with 95% CI. Heterogeneity was assessed using the I² statistic.

Results 8969 records were retrieved and nine RCTs (61 records) were ultimately included (n=8818 participants). Two RCTs recruited high-risk patients, two RCTs recruited intermediate-risk patients, two RCTs recruited low-risk patients, one RCT recruited high-risk (>70 years) or any-risk (>80 years) patients; and two RCTs recruited all-risk or ‘operable’ patients. While there was no overall change in the risk of dying from any cause (30 day: RR 0.89, 95% CI 0.65 to 1.22; ≤1 year: RR 0.90, 95% CI 0.79 to 1.03; 5 years: RR 1.09, 95% CI 0.98 to 1.22), cardiovascular mortality (30 day: RR 1.03, 95% CI 0.77 to 1.39; ≤1 year: RR 0.90, 95% CI 0.76 to 1.06; 2 years: RR 0.96, 95% CI 0.83 to 1.12), or any type of stroke (30 day: RR 0.83, 95% CI 0.61 to 1.14; ≤1 year: RR 0.94, 95% CI 0.72 to 1.23; 5 years: RR 1.07, 95% CI 0.88 to 1.30), the risk of several clinical outcomes was significantly decreased (major bleeding, AKI, NOW-AF) or significantly increased (major vascular complications, PPM implantation) for TAVI versus SAVR across different risk levels, especially in low-risk patients and in key subgroups of interest.

Strengths and limitations of this study

This systematic review (SR) assesses two treatments (transcatheter aortic valve implantation (TAVI) vs surgical aortic valve replacement, SAVR) for patients with severe aortic stenosis.

Aims to support shared decision making by presenting evidence across a broad range of treatment outcomes, a wide range of surgical risk levels and a uniquely large number of subgroups which can inform decision-making of individual patients.

Patients were involved in an initial needs assessment based on their priorities and experience, which ultimately evolved into the prespecified outcomes of interest.

Methods follow guidance by Cochrane, the Centre for Reviews and Dissemination as well as the Preferred Reporting Items for Systematic Reviews and Meta-Analyses reporting guideline and the SR was registered on PROSPERO.

Includes several new randomised controlled trials or long-term study outcomes that have not yet been incorporated into pooled analysis for TAVI versus SAVR.
to −1.29; 4 RCTs, n=2758 participants). Subgroup analysis generally favoured TAVI patients receiving implantation via the transfemoral (TF) route (vs non-TF); receiving a balloon-expandable (vs self-expanding) valve; and those at low-intermediate risk (vs high risk). All RCTs were rated at high ROB, predominantly due to lack of blinding and selective reporting.

Conclusions No overall change in the risk of death from any cause or cardiovascular mortality was identified but 95% CIs were often wide, indicating uncertainty. TAVI may reduce the risk of certain side effects while SAVR may reduce the risk of others. Most long-term (5-year) results are limited to older patients at high surgical risk (ie, early trials), therefore more data are required for low risk populations. Ultimately, neither surgical technique was considered dominant, and these results suggest that every patient with SAS should be individually engaged in SDM to make evidence-based, personalised decisions around their care based on the various benefits and risks associated with each treatment. PROSPERO registration number CRD42019138171.

INTRODUCTION
In the pretranscatheter aortic valve implantation (TAVI) era, patients with severe degenerative symptomatic aortic stenosis (SAS) at high surgical risk had limited access to treatment options, as surgical aortic valve replacement (SAVR) was considered to have an unacceptably elevated risk of complications or death.1 TAVI was developed as a lower impact, minimally invasive surgical alternative to provide such patients with a much-needed therapeutic option to ameliorate disease symptoms and improve quality of life. TAVI is now being more widely discussed as a useful option for patients at intermediate or even lower levels of surgical risk.

While guidelines do not yet formally recommend TAVI as a first-choice therapy in low-risk patients,2–4 several new trials have recently reported promising early- and mid-term data for patients at lower levels of risk. However, current evidence suggests that clinical practice has not yet effectively incorporated TAVI into shared decision making (SDM) processes in patients with SAS who are at lower levels of risk.5 The use of decision aids in SDM for patients with SAS has been shown to increase patient knowledge and satisfaction.6 Yet the provision of too little information within decision aids is frequently described by patients as a critical barrier to the SDM process.5 Therefore, the aim of our systematic review (SR) was to generate a highly accessible and comprehensive dataset that clearly described the current evidence around the risks that may be associated with TAVI versus SAVR.

Several recent SRs and meta-analyses (MAs) have been published that compare patient outcomes following TAVI versus SAVR.7–9 For example, Barili et al and Wang et al reported exclusively on all-cause mortality, and indicated similar risks of death for TAVI vs SAVR at early time points.7 8; Barili et al further reported that at late time points (40 months), all-cause mortality was higher for TAVI vs SAVR.7 In initial consultations carried out in our clinic (which informed the final outcomes investigated by our study), patients indicated that they wanted to consider outcomes beyond the risk of death from any cause. This highlighted a clear need for a SR and MA that included a broad range of outcomes beyond mortality, and reported results in an accessible way to enable the evidence and conclusions to be used directly in a SDM context. We also identified that extensive subgroup analysis by route of TAVI, level of surgical risk and valve type across all patient outcomes was largely absent in recent SRs and MAs, and yet was considered by our team to be critical, since these three factors can, in large part, be dictated by issues such as patient frailty; anatomical restrictions that limit transfemoral (TF) access, precluding a TF-first approach; and policies and practices that are implemented at either the national or institutional level that govern which valves are available. Finally, we aimed to incorporate new trial data from the UK TAVI study10 11 which has not, to our knowledge, been incorporated into any existing MAs.

The ultimate goal of this study was to generate accessible data that could be used by patients, together with their doctors, to make tailored treatment decisions based on the types of benefits and risks they were willing to accept. This SR was performed as part of a wider project to implement a formal decision aid-based SDM process for patients at the University Hospital of Kiel using the most up-to-date, comprehensive and methodologically rigorous evidence available.12

METHODS
This SR was carried out in accordance with the methodologies recommended by Cochrane15 and the Centre for Reviews and Dissemination14 following Preferred Reporting Items for Systematic Reviews and Meta-Analyses reporting guidelines.15 16

Search strategy and selection criteria
In order to identify relevant studies, several databases were searched from January 2000 to August 2020, including MEDLINE, In-Process & Other Non-Indexed Citations, Daily Update, Epub Ahead of Print (Ovid), Embase (Ovid) and Cochrane Central Register of Controlled Trials (CENTRAL; Wiley). The lower search date limit (2000) was set 2 years earlier than the first-in-man report of the TAVI procedure.17 Searches used a combination of text and database thesaurus terms. The search strategies were adapted to each resource and no limits or restrictions on language or publication status were applied. Reference lists of included articles were searched to identify additional studies. All search strategies are provided in online supplemental appendix S1.

Key inclusion criteria were defined using a Population, Intervention, Comparator, Outcome, Study Design approach. The population of interest was patients with severe aortic valve stenosis. The intervention of interest was TAVI compared with SAVR. Only randomised controlled trials (RCTs) were included to ensure that the conclusions and findings of the review were based on the best available evidence.

Titles and abstracts identified through electronic database and web searching, and subsequently full paper...
copies of all potentially eligible references were screened independently by two reviewers; any disagreements were resolved by discussion. No restrictions were placed on language or publication status.

Data extraction
Microsoft Excel was used to compile data extraction sheets. Data extraction was performed by two reviewers. One reviewer extracted the data while the second reviewer checked the extractions. Any discrepancies were resolved by discussion or the intervention of a third reviewer.

Outcomes of interest
Primary outcomes included: all-cause or cardiovascular mortality. Secondary outcomes included: length of stay in intensive care unit (ICU) or hospital; valve durability; reintubation/reintervention; stroke (any stroke or major/disabling stroke); myocardial infarction (MI); major vascular complications; major bleeding; permanent pacemaker (PPM) implantation; new-onset or worsening atrial fibrillation (NOW-AF); endocarditis; acute kidney injury (AKI); recovery time and pain. These were included for all time points up to the longest available. Additional methodological details are reported in the online supplemental appendix.

We originally aimed to identify evidence on additional secondary outcomes (including: minor or non-disabling stroke; symptoms such as dyspnoea; 6 min walk test; exercise intensity; exercise duration; impact on activities of daily living; impact on family and carers; health-related quality of life (EQ-5D; KCCQ; SF-12; SF-36); and inconvenience/costs from treatment (eg, need for rehabilitation)), but ultimately had to streamline the final outcomes of interest (after the full-text screening stage) due to budget restraints.

Risk of bias
The risk of bias (methodological quality) of each included study was assessed using the Cochrane Risk of Bias Tool for RCTs. Risk of bias assessment was performed by one reviewer and checked by a second reviewer. Any discrepancies were resolved by discussion or the intervention of a third reviewer.

Data synthesis and statistical analysis
All MAAs were conducted using random-effects models. Dichotomous outcomes (eg, proportion of patients experiencing each type of outcome) were assessed using the Mantel-Haenszel method applying random-effects models to generate a risk ratio (RR) with 95% CI. Continuous outcomes were assessed using inverse variance applying random-effects models to generate a mean difference with 95% CI. If studies reported time-to-event outcomes, these were planned to be reported as hazard ratios (HRs) with 95% CI; however, this type of data was not identified. The selection of random-effects and fixed-effect models was made based on a judgement of both clinical and statistical heterogeneity.

We further presented our narrative results in an accessible way by calculating the rates from MAAs (intervention vs comparator) and transforming these into absolute numbers (and percentages of these; X/100 (%)) so that patients might be better able to understand them (following the International Patient Decision Aid Standards criteria for patient decision aids). The desire to report our results in a patient-accessible way also informed our choice of effect estimates, since presenting the data in this way would not have been possible with HRs or ORs. For dichotomous outcomes, no evidence of a difference in the effect estimate was set at ≥0.9 to ≤1.1. Statistical significance was considered at p≤0.05. Pooled effect sizes and 95% CIs were only presented where there were two or more trials that were considered to be clinically and statistically homogeneous. The judgement of clinical heterogeneity was based on baseline characteristics of the trial populations (eg, age, gender). Statistical heterogeneity was assessed using the I² statistic. For the purposes of this review, a simplified categorisation of heterogeneity was used: low (0% to 25%), moderate (26% to 75%) and high (≥75%). Sensitivity analyses were considered in cases where high statistical or clinical heterogeneity was present.

We preferentially used the intention-to-treat (ITT) population, where reported. For major bleeding, we preferentially used the definition of ‘life-threatening or disabling bleeding’, where available. For AKI, we preferentially used the definition, ‘stage 2–3 AKI’, where available. All MAAs were double-checked by a second reviewer. Forest plots for the main analyses were grouped by the stated study risk level, as defined by the study inclusion criteria; subgroup analyses by level of surgical risk were based exclusively on Society of Thoracic Surgeons Predicted Risk of Mortality (STS-PROM) scores within each study.

Subgroup analysis was prespecified based on TAVI route (TF vs non-TF), level of surgical risk (based on absolute STS-PROM scores) and valve type (balloon vs self-expanding).

All MAAs were performed using Review Manager V.5.3. Publication bias was planned to be assessed where there were sufficient numbers of trials (ie, a minimum of ten trials), in line with published recommendations.

Patient and public involvement
Patients were involved in an initial needs assessment based on their priorities and experience, which ultimately evolved into our prespecified outcomes of interest. Patients were not involved in the formal design, conduct, analysis or reporting of this study.

RESULTS
Search results
We searched three main databases, and retrieved a total of 8969 records. Eight additional records were identified from reference checking included studies, and two records were identified by clinical experts. After deduplication, 6082 records remained. The flow of studies through the search and screening processes is summarised in figure 1.

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Open access
In total, 6082 records were screened based on the title and abstracts; 105 were ordered for full text screening and 5977 were excluded. After the full-text screening stage, 61 records (9 studies) were identified for inclusion in the review.

Baseline characteristics of included studies
Nine RCTs (61 records; most studies had more than one associated publication) with a total of 8818 patients were identified that fit the inclusion criteria (table 1). Inclusion and exclusion criteria are provided in online supplemental table S1. Primary and secondary outcomes are provided in online supplemental table S2.

In terms of the disease of interest, all nine studies reported recruiting patients with SAS (table 1, online supplemental table S3). In terms of the level of surgical risk at the study level (which was based on the multifaceted, study-specific definitions provided in online supplemental table S3), two studies reported recruiting low-risk patients (EVOLUT, PARTNER 3), two studies reported recruiting intermediate-risk patients (PARTNER 2A, SURTAVI), two studies reported recruiting high-risk patients (PARTNER 1A, US CoreValve), one study reported recruiting intermediate-to-high-risk (≥70 years) or any risk (≥80 years) patients (UK-TAVI), one study reported recruiting patients across all levels of risk (NOTION) and one study simply reported that patients should be ‘operable’ (STACCATO) (table 1, online supplemental table S3). The definitions of surgical risk varied substantially between studies (online supplemental table S3). In terms of the valve type, four of nine studies (50%) reported using a self-expanding valve, four of nine studies (50%) reported using a balloon-expandable valve, and one of nine studies reported using any type of CE-marked valve (table 1).

Publication bias
It was not possible to assess publication bias due to the relatively small number of included studies (<10).20

Risk of bias assessment
All nine studies were assessed for risk of bias using the Cochrane risk of bias tool for RCTs, which contains eight assessment domains.13 Two studies had five domains at high risk of bias (SURTAVI, UK TAVI); five studies had four domains at high risk of bias (NOTION, PARTNER 1A, PARTNER 2A, PARTNER 3, STACCATO); and two studies had three domains at high risk of bias (EVOLUT, US CoreValve) (table 2). All studies were rated at high risk of bias for blinding bias.
Table 1  Study characteristics

| Study ID*, linked publications | Recruit-ment dates | Total sample size | Disease | Patient age (years)† | Level of surgical risk‡ | TAVI route | Valve type(s) | Valve name | Funding source |
|-------------------------------|-------------------|-------------------|---------|----------------------|-------------------------|------------|--------------|------------|----------------|
| **High risk**                 |                   |                   |         |                      |                         |            |              |            |                |
| PARTNER 1A [20-25]           | May 2007 to Aug 2009 | 699               | SAS and cardiack symptoms | Not prespecified | TAVI: 11.8 (3.3); SAVR: 11.7 (3.5) | TF-first; TA if vascular access was limited | Balloon-expandable | Edwards Sapien | Pharma (EW) |
| US CoreValve [26-31]         | Feb 2011 to Sep 2012 | 797               | SAS and heart failure symptoms | No limits | TAVI: 7.3 (3.0); SAVR: 7.5 (3.4) | TF or non-TF (SC or direct aortic) | Self-expanding | MDT CoreValve | Pharma (MDT) |
| **Intermediate risk**         |                   |                   |         |                      |                         |            |              |            |                |
| UK TAVI [32-34]              | Apr 2014 to Apr 2018 | 913               | Symptomatic SAS | ≥80 or ≥70† | TAVI: 2.6 (2.0 to 3.5); SAVR: 2.7 (2.0 to 3.4) | TF, TA, SC, direct aortic | Any CE-marked valve | SAPIEN, SAPIEN XT, SAPIEN 3 (all EW); CoreValve, Evolut/ Evolut R, Evolut Pro (all MDT); Lotus, Symetis Acurate/Neo (all BSX); Other (Portico, Direct Flow Medical) | Public/government (NIHR) |
| PARTNER 2 A2134 [31-38]      | Dec 2011 to Nov 2013 | 2032              | SAS | No limits | TAVI: 5.8 (2.1); SAVR: 5.8 (1.9) | TF or transthoracic (TA or TAO) | Balloon-expandable | SAPIEN XT (EW) | Pharma (EW) |
| SURTAVI [39-40]              | Jun 2012 to Jun 2016 | 1660              | Symptomatic SAS | No limits | TAVI: 4.4 (1.5); SAVR: 4.5 (1.6) | TF-first; SC or TAO in the case of unsuitable iliofemoral anatomy | Self-expanding | CoreValve, Evolut R (all MDT) | Pharma (MDT) |
| **Low risk**                 |                   |                   |         |                      |                         |            |              |            |                |
| EVOLUT [41-43]               | Mar 2016 to Nov 2018 | 1468              | SAS | No limits | TAVI: 1.9 (0.7); SAVR: 1.9 (0.7) | TF, subclavian or TAO | Self-expanding | CoreValve, Evolut R, Evolut PRO (all MDT) | Pharma (MDT) |
| PARTNER 3 [44-47]            | Mar 2016 to Oct 2017 | 950               | SAS | No limits | TAVI: 1.9 (0.7); SAVR: 1.9 (0.6) | TF | Balloon-expandable | SAPIEN 3 (EW) | Pharma (EW) |
| **All risk**                 |                   |                   |         |                      |                         |            |              |            |                |
| NOTION [48-55]               | Dec 2009 to Apr 2014 | 280               | Degenerative SAS | ≥70 | TAVI: 79.2 (4.9); SAVR: 79.1 (4.7) | TAVI: 2.9 (1.6); SAVR: 3.1 (1.7) | TF-first; left SC access considered when the TF route not accessible | Self-expanding | CoreValve (MDT) | Charity (The Danish Heart Foundation) |
| STACCATO [56-63] [64-65]     | Nov 2008 to May 2011 | 70                | SAS | Initially ≥70; later modified to ≥75 | TAVI: 80 (3.6); SAVR: 82 (4.4) | ‘Operable’ TAVI: 3.1 (1.5); SAVR: 3.4 (1.2) | TF | Balloon-expandable | Edwards Sapien | Public/government (University, DHF) |

All studies are randomised controlled trials, as per our inclusion criteria.

*Main publication provided.
†Mean (SD) are provided.
‡STS-PROM scores are provided (mean (SD)).
§Median and IQR.
¶If patients are considered at intermediate or high operative risk from conventional AVR by a multidisciplinary heart team.
AVR, aortic valve replacement; BSX, Boston Scientific; CE, Conformité européenne; DHF, Danish Heart Foundation; EW, Edward Lifesciences; MDT, Medtronic; NA, not applicable; NIHR, National Institute for Health Research; NYHA, New York Heart Association; SAS, severe aortic stenosis; SAVR, surgical aortic valve replacement; SC, subclavian; STS, society for thoracic surgeons; STS-PROM, Society of Thoracic Surgeons Predicted Risk of Mortality; TA, transapical; TAO, transaortic; TAVI, transcatheter aortic valve implantation; TF, transfemoral.
of participants, blinding of personnel and other biases. Other biases were typically based on a disparity between the number of patients randomised versus the number of patients implanted per treatment arm (where a greater proportion of TAVI patients tended to receive their assigned implant compared with SAVR patients) or a disparity between the numbers of patients who crossed over per treatment arm.

Clinical outcomes
A visual overview of all main results is presented in figure 2, and a tabular overview of all main results is presented in table 3.

Mortality
All-cause mortality
The risk of dying from any cause either within the periprocedural period (which was typically defined as before, during or soon after surgery) or during the in-hospital stay was numerically increased by 16% for TAVI compared with SAVR (RR 1.16, 95% CI 0.52 to 2.27. p=0.67, I² 0%; 3 studies, n=3732 patients); however, this was not a statistically significant difference (figure 3). No heterogeneity was evident in this analysis.

The risk of dying from any cause by 30 days following surgery was numerically decreased by 15% for TAVI compared with SAVR (RR 0.89, 95% CI 0.65 to 1.22. p=0.48, I² 14%; 9 studies, n=8873 patients); however, this was not a statistically significant difference. Heterogeneity was moderate for intermediate-risk and all-risk studies at 30 days.

There was no evidence of a difference in the overall risk of dying from any cause by 1 year following surgery (RR 0.90, 95% CI 0.79 to 1.03. p=0.13, I² 0%; 8 studies, n=8831 patients) or by 2 years (RR 0.90, 95% CI 0.76 to 1.06. p=0.20, I² 0%; 8 studies, n=8831 patients) or by 5 years (RR 1.09, 95% CI 0.98 to 1.22. p=0.10, I² 48%; 5 studies, n=3866 patients). Heterogeneity was moderate at 2 years and 5 years in high-risk studies.

At 6 years following surgery, a single small study reported that the risk of dying from any cause was numerically increased by 12% for all-risk TAVI patients compared with all-risk SAVR patients (RR 1.12, 95% CI 0.84 to 1.50. p=0.43, I² N/A; 1 study, n=27425); however, this was not a statistically significant difference. Across study risk groups (defined by the criteria reported in online supplemental table S3, which were not exclusively based on STS-PROM scores), the CIs overlapped between each group at all time points, suggesting no significant difference between study risk groups (figure 3).

Cardiovascular mortality
There was no evidence of a difference in the risk of dying from cardiovascular or cardiac causes for TAVI compared with SAVR by 30 days following surgery (RR 1.03, 95% CI 0.77 to 1.39. p=0.43, I² 0%; 1 study, n=27425); however, this was not a statistically significant difference. Across study risk groups, the CIs overlapped between each group at all time points, suggesting no significant difference between study risk groups (figure 3).
2 years (RR 0.96, 95% CI 0.83 to 1.12, p=0.61, I² 0%; 5 studies, n=5503 patients) (figure 4). Heterogeneity was low at 30 days and moderate for high-risk studies at 1 and 2 years.

By 5 years following surgery, the overall risk of dying from cardiovascular or cardiac causes was significantly increased by 11% for TAVI compared with SAVR (RR 1.11, 95% CI 1.01 to 1.23, p=0.04, I² 0%; 4 studies, n=3761 patients).
| Outcome                                   | In-hospital/periprocedural (RR (95% CI)) | 30 days (RR (95% CI)) | 1 year (RR (95% CI)) | 2 years (RR (95% CI)) | 5 years (RR (95% CI)) |
|--------------------------------------------|----------------------------------------|----------------------|---------------------|----------------------|----------------------|
| All-cause mortality                        | Favours SAVR                           | 1.16 (0.59 to 2.27; 9 studies, n=3732) | No difference       | No difference         | No difference         |
| Cardiovascular mortality                   | NR                                     | No difference        | No difference       | No difference         | No difference         |
| All stroke                                | Favours TAVI                           | 0.80 (0.40 to 1.62; 1 study, n=750)  | No difference       | No difference         | No difference         |
| Major or disabling stroke                  | NR                                     | No difference        | No difference       | No difference         | No difference         |
| Myocardial infarction                      | Favours SAVR                           | 1.38 (0.23 to 8.20; 1 study, n=750)  | No difference       | No difference         | No difference         |
| Major bleeding                             | Favours TAVI                           | 0.41 (0.28 to 0.60; 2 studies, n=1026) | No difference       | No difference         | No difference         |
| Major vascular complications               | Favours SAVR                           | 3.83 (1.69 to 8.67; 2 studies, n=1026) | No difference       | No difference         | No difference         |
| Permanent pacemaker implantation           | Favours SAVR                           | 7.19 (3.11 to 16.62; 1 study, n=750)  | No difference       | No difference         | No difference         |
| Acute kidney injury                        | Favours TAVI                           | 0.30 (0.10 to 0.93; 2 studies, n=1026) | No difference       | No difference         | No difference         |
| New-onset or worsening atrial fibrillation | Favours TAVI                           | 0.23 (0.06 to 0.91; 2 studies, n=1536) | No difference       | No difference         | No difference         |
| Endocarditis                               | NR                                     | No difference        | No difference       | No difference         | No difference         |
| Reintervention/reoperation                 | Favours SAVR                           | 4.59 (0.22 to 95.32; 1 study, n=750)  | No difference       | No difference         | No difference         |
patients). Heterogeneity was low at 5 years. By study risk group (defined by the criteria reported in online supplemental table S3), which were not exclusively based on STS-PROM scores), the CIs overlapped between each group at all time points, suggesting no significant difference between study risk groups (figure 4).

All stroke
A single study reported that the risk of having any type of stroke at periprocedural time points was numerically decreased by 20% for TAVI compared with SAVR (RR 0.80, 95% CI 0.4 to 1.62, p=0.54, I² N/A; 1 study, n=750 patients)21; however, this was not a statistically significant difference (figure 5).

The risk of having any type of stroke was numerically decreased by 18% for TAVI compared with SAVR by 30 days following surgery (RR 0.83, 95% CI 0.61 to 1.14, p=0.26, I² 36%; 9 studies, n=8873 patients)10 21–28 and by 12% by 2 years (RR 0.88, 95% CI 0.67 to 1.16, p=0.37, I² 48%; 6 studies, n=6, 453 patients)21–23 25 26 28; however, these differences were not statistically significant.

There was no evidence of a difference in the risk of having any type of stroke by 1 year following surgery (RR 0.94, 95% CI 0.72 to 1.23, p=0.65, I² 48%; 8 studies, n=8831 patients)10 21–26 28) or by 5 years (RR 1.07, 95% CI 0.88 to 1.30, p=0.51, I² 11%; 4 studies, n=3761 patients)21 23 25 26. Heterogeneity was moderate at 30 days, at 1 year; high for high-risk studies and moderate for intermediate-risk studies at 2 years; and low at 5 years. By study risk group (defined by the criteria reported in online supplemental table S3, which were not exclusively based on STS-PROM scores), the CIs overlapped between each group at all time points, suggesting no significant difference in the risk of all stroke between study risk groups (figure 5).

Other outcomes
The risk of major or disabling stroke was numerically decreased by 15%–21% for TAVI compared with SAVR between 30 days to 2 years following surgery (although this was not a statistically significant difference); there was no evidence of a difference in risk at 5 years (online supplemental figure 1). The risk of MI was numerically increased by 38% at periprocedural time points, but numerically decreased by 16% at 30 days following surgery; there was no evidence of a difference in risk of MI between 1 and 5 years following surgery (online supplemental figure 2). The risk of major bleeding was significantly decreased by between 20% and 63% for TAVI compared with SAVR at all time points between periprocedural and 5 years following surgery (online supplemental figure 3; sensitivity analysis based on definition of major bleeding presented in online supplemental figure 4). The risk of major vascular complications was significantly increased by between 205% and 383% for TAVI compared with SAVR at all time points between periprocedural and 5 years following surgery (online supplemental figure 5). The risk of PPM implantation was significantly increased by between 190% and 719%
Figure 3  Forest plots for death from any cause. (A) In-hospital or periprocedural, (B) 30 days, (C) 1 year, (D) 2 years, (E) 5 years, and (F) 6 years time points are presented. Risk subgroups represent the study risk level and not necessarily the patient risk level. M-H, Mantel-Haenszel; SAVR, surgical aortic valve replacement; TAVI, transcatheter aortic valve implantation.

Figure 4  Forest plots for death from cardiovascular causes. (A) 30 days, (B) 1 year, (C) 2 years and (D) 5 years time points are presented. Risk subgroups represent the study risk level and not necessarily the patient risk level. M-H, Mantel-Haenszel; SAVR, surgical aortic valve replacement; TAVI, transcatheter aortic valve implantation.
for TAVI compared with SAVR at all time points between periprocedural and 5 years following surgery (online supplemental figure 6). The risk of AKI was significantly decreased by between 42% and 70% for TAVI compared with SAVR at all time points between periprocedural time points and 2 years following surgery (online supplemental figure 7). The risk of NOW-AF was significantly decreased by between 55% and 77% for TAVI compared with SAVR for all time points between periprocedural and 5 years following surgery (online supplemental figure 8). The risk of endocarditis varied between being numerically reduced (30 days), no different (1 year, 2 years, 6 years) or numerically increased (5 years) for TAVI compared with SAVR (online supplemental figure 9). The risk of reintervention or reoperation was numerically increased by 154%–459% for TAVI versus SAVR from periprocedural time points up to 1 year following surgery; and was significantly increased by 278% for TAVI vs SAVR by 2 years following surgery (online supplemental figure 10). The risk of rehospitalisation varied between being numerically reduced (30 days), no different (1 year), numerically increased (2 years) or significantly increased (5 years) for TAVI compared with SAVR (online supplemental figure 11). The length of stay in the ICU and the overall length of hospital stay were generally shorter for TAVI compared with SAVR (online supplemental figure 12, tables S4 and S5).

**Subgroup analysis**

For the primary outcome of all-cause mortality, subgroup results generally suggested that patients at low or intermediate risk (based exclusively on STS-PROM scores alone) had a significantly lower risk of dying from any cause after TAVI compared with patients at high risk from 1 to 5 years following surgery (online supplemental table S6); and that patients who had TAVI through the TF route had a significantly lower risk of dying from any cause compared with patients who had TAVI through a non-TF route from 30 days to 5 years following surgery (online supplemental table S7).

For the primary outcome of cardiovascular mortality, subgroup results generally suggested that patients at low or intermediate risk (based exclusively on STS-PROM scores alone) had a significantly higher risk of dying from cardiovascular causes after TAVI compared with patients at high risk by 1 year following surgery (online supplemental table S6); and that patients who had TAVI through the TF route had a significantly lower risk of dying from cardiovascular causes than patients who had TAVI through a non-TF route from 30 days to 5 years following surgery (online supplemental table S7). Results for the subgroup analysis by valve type for the outcome ‘new PPM implantation’ are presented in online supplemental table S8, showing higher rates for self-expanding TAVI compared with balloon expandable TAVI.

For any-stroke outcomes, subgroup results generally suggested that patients at low or intermediate risk (based exclusively on STS-PROM scores alone) had a significantly higher risk of any type of stroke after TAVI compared with patients at high risk by 1 year following surgery (online supplemental table S6); and that patients who had TAVI through the TF route had a lower risk of any type of stroke than patients who had TAVI through...
a non-TF route from 30 days to 5 years following surgery (online supplemental table S7).

Valve durability of the two treatments was comparable. However, NOTION reported a statistically significantly lower rate of moderate/severe haemodynamic structural valve deterioration after 6 years follow-up, see online supplemental table S9.

Sensitivity analysis
As we noted an inconsistency in how studies reported subgroup data by level of surgical risk, we performed sensitivity analyses to address this. Most studies reported two subgroups based on low-intermediate vs high risk (NOTION (STS <3% vs STS ≥3%); PARTNER 1A (STS ≤11 vs STS >11); US CoreValve (STS-PROM ≤7 vs STS-PROM >7)); however, one study reported three subgroups based on low-risk, intermediate-risk and high-risk (SURTAVI (STS <3% vs STS ≥3% to<5% vs STS ≥5%)). Therefore, we combined low-risk and intermediate-risk groups to make the data more comparable across studies.

To test whether this affected the outcome, we performed sensitivity analyses where we assigned subgroups to low vs high instead of low- intermediate versus high for the SURTAVI study. For most outcomes, this did not change the direction of the effect or push the result into or out of significance. However, for reintervention/reoperation, the comparison of low versus high was significant (RR 5.79, 95% CI 1.19 to 28.31, p=0.03; 1 study, n=384 patients) whereas the comparison of low-intermediate versus high was not (RR 3.11, 95% CI 0.72 to 13.48, p=0.13; 1 study, n=864 patients). Conversely, for all stroke, the comparison of low-intermediate versus high was significant (RR 0.54, 95% CI 0.31 to 0.97, p=0.04; 1 study, n=864 patients) whereas the comparison of low vs high was not (RR 0.51, 95% CI 0.19 to 1.33, p=0.17; 1 study, n=384 patients). Similarly, for PPM implantation, the comparison of low-intermediate versus high was significant (RR 1.41, 95% CI 1.08 to 1.83, p=0.01; 1 study, n=864 patients) whereas the comparison of low versus high was not (RR 1.12, 95% CI 0.77 to 1.65, p=0.55; 1 study, n=384 patients).

DISCUSSION
Strengths and limitations
SDM is a critical form of professional–patient interaction that enables patients to make informed and uniquely personal decisions on their own care using evidence-based medical information. SRs and MAs provide important evidence to inform and generate a comprehensive overview pertaining to a particular research question, and therefore may naturally feed into decision aids and SDM-based patient–physician communication. This SR includes data from a new study (UK TAVI), plus long-term data from several other studies (EVOLUT, PARTNER 2, PARTNER 3). Our MAs have revealed several critical differences in clinical outcomes for TAVI compared with SAVR that should be highlighted and carefully considered when patients, together with their physicians, are making decisions regarding treatment options for SAS.

While the STACCATO trial was terminated early due to safety concerns, we nevertheless included these data in our analysis as the study met our inclusion/exclusion criteria. This is in line with the approaches of several other SRs.\(^29-33\) We performed sensitivity analyses to test whether the inclusion of the STACCATO study impacted any main analyses; this did not change the direction or statistical significance of any results (data not shown).

Regarding study-level surgical risk, the two high-risk studies included in our analyses (PARTNER 1A, US CoreValve) recruited elderly (mean age >83 years) patients at increased risk of intraoperative death or death within 30 days of the procedure. These risk levels were further elevated by including high proportions of patients who had undergone previous coronary artery bypass graft (CABG) surgeries in the SAVR arms of both studies (44.2% (PARTNER 1A) or 30.2% (US CoreValve)). The two intermediate-risk studies included in our analyses (PARTNER 2A, SURTAVI) might be expected to produce more representative results based on recruiting larger numbers of slightly younger patients (mean age >79 years), fewer of whom in the SAVR arm had previously undergone CABG (25.6% (PARTNER 2A) or 16.7% (SURTAVI)). The results from the two low-risk studies included in our analyses (EVOLUT, PARTNER 3), which recruited relatively young patients (mean age >73 years), are of key interest to the field. While these studies actively excluded patients with prior cardiac surgery, they nevertheless included patients who underwent concomitant surgical procedures (26.4% (PARTNER 3) or 13.6% (EVOLUT)). Therefore, in all studies, the inclusion of patients who had undergone prior cardiac procedures may have introduced bias (or at least clinical heterogeneity) that may have been disadvantageous to the SAVR arm, as surgical redo aortic valve procedures typically confer a higher risk of mortality compared with primary surgeries, a difference that does not manifest per se in patients receiving the TAVI procedure.

No overall change in the risk of death from any cause was identified for TAVI compared with SAVR; however, CIs around the point estimates for low risk and all-risk studies were often wide, which introduced substantial uncertainty. Follow-up duration is currently relatively short for low-risk studies, and longer-term data will be of great relevance to future updates of this review. For example, 5-year all-cause mortality data have recently been published for the intermediate-risk PARTNER 2A study;\(^34\) however, 5-year data for the intermediate-risk SURTAVI study are still outstanding. A significant increase was observed in the risk of dying from cardiovascular or cardiac causes for TAVI vs SAVR at 5 years.

Of note, TAVI was associated with a significantly lower risk of major bleeding, NOW-AF and AKI compared with SAVR. Patients also spent fewer days in the ICU and in hospital overall after TAVI compared with SAVR. In contrast, TAVI appeared to be associated with a
significantly increased risk of major vascular complications and new PPM implantations at all time points following surgery; and a significantly increased risk of rehospitalisation or reintervention/reoperation at late time points compared with SAVR.

Based on subgroup analyses, patients undergoing TAVI via the TF route generally had improved outcomes compared with patients undergoing TAVI via the non-TF route (with the exception of major vascular complications); and patients at low or intermediate risk (based exclusively on STS-PROM scores) generally had improved outcomes compared with patients at high risk (with the exception of new PPM implantation or reintervention/reoperation).

In terms of valve durability, we identified three studies (NOTION, PARTNER 1A, US CoreValve) that either reported no cases of structural valve deterioration in TAVI or SAVR patients at 5 years (PARTNER 1A); mixed outcomes depending on the definition of valve deterioration used (ranging from significantly lower rate of haemodynamic structural valve deterioration for TAVI patients compared with SAVR patients at 6 years (based on one definition) to no difference between TAVI vs SAVR (based on three separate definitions) at 6 years (NOTION); or no cases of valve frame fracture in 21 TAVI patients who had undergone implant explantation or autopsy after death a median of 17 days (range: 0–503 days) after implantation (US CoreValve). Thus, there was only limited and heterogeneous evidence to inform this outcome, and further research into the long-term durability of the TAVI valves is clearly required.

No evidence comparing TAVI vs SAVR was identified for recovery time or pain, therefore further research is needed to address these areas of interest.

We noted several study limitations. A major limitation was a discrepancy in the number of events reported for the same time point in different publications within the same study series. For example, in the PARTNER study, Smith 2011 reported 1-year MI as one event in the TAVI arm (out of n=348) and two events in the SAVR arm (out of n=351), while Kodali et al reported 1-year MI as zero events in the TAVI arm (out of n=348) and two events in the SAVR arm (out of n=351). In these cases, we chose to use the first published set of numbers reported for consistency. Several studies (EVOLUT, SURTAVI) only reported percentages of patients experiencing an event based on an estimated incidence derived from a Bayesian analysis rather than absolute numbers. This was an issue for pooled data analysis, as absolute values had to be estimated from already-estimated values, compounding any potential numerical variation.

Multiple studies that prespecified reporting the ITT population in a sensitivity analysis failed to do this across all published time points. While we used ITT as our preferred analysis population, this meant that in some cases, only the as-treated population was available for pooled analysis, which may have contributed to heterogeneity.

Most studies were only powered for the primary outcome, which was generally read out at 12 or 24 months. This meant that long-term results and durability analyses in particular may have been underpowered. For all outcomes except all-cause mortality, subgroup analysis by level of surgical risk was also only reported at 1 year, preventing any longitudinal analyses.

The clinical relevance of some of the acute procedural outcomes, such as NOW-AF, was in some cases uncertain. It was often not clearly reported whether such clinical symptoms had recovered, such as converting to a sinus rhythm, or whether long-term sequelae were present.

There was substantial variation in the definitions used by each study for certain outcomes, which impacted study comparability and increased clinical heterogeneity. For example, ‘major bleeding’ was reported under several definitions, including life-threatening or disabling bleeding (EVOLUT, PARTNER 2A, PARTNER 3, US CoreValve), major bleeding (PARTNER 1A, US CoreValve), life-threatening, disabling or major bleeding (PARTNER 3), life-threatening or major bleeding (SURTAVI) or simply ‘bleeding’ (STACCATO). Only two studies reported two different definitions of bleeding (PARTNER 3 (life-threatening or disabling bleeding and life-threatening, disabling or major bleeding); and US CoreValve (life-threatening or disabling bleeding and major bleeding)).

Finally, we have only focused on RCTs in our SR, as we considered this to be the highest level of available evidence. We acknowledge that other levels of evidence (such as large registries and propensity-score matched datasets) are available, with more patients reported, especially for longer follow-up periods. However, only one of these sources reported information for low-risk patients. The number of patients at risk is rather small at 5 years and this evidence is based on studies with considerable differences in baseline characteristics (e.g. post-malignant disease) that might account for the long-term differences in outcomes. The other two sources provide data for high-risk patients only and do not include many more patients than the RCTs identified in our SR. Several potential sources of bias (misdosing, no data/deaths out of hospital, different time intervals for outcome assessments) could lower the level of evidence even further, especially when compared with results obtained in RCTs.

Ongoing studies

Three ongoing studies with no published data at the time of our literature searches were identified during screening: DEDICATE, RHEIA and VIVA. The DEDICATE study is currently recruiting patients with SAS at low-to-intermediate levels of surgical risk to analyse whether TAVI is non-inferior to SAVR. The RHEIA study will recruit female patients with SAS who are at any level of surgical risk to determine whether TAVI may be more effective than SAVR. The VIVA study will recruit patients with SAS and a small aortic annulus to compare TAVI vs SAVR in this specific subpopulation.
Comparison with other SRs

We identified at least 18 previous SRs that compared TAVI vs SAVR in patients with SAS. One SR/MA was identified that reported a difference in findings in terms of mortality based on a pooled analysis of RCT and observational studies. However, this discrepancy disappeared when only RCT study data were considered (ie, results were similar when based on the most robust evidence base). None of these studies incorporated new UK TAVI study data; none analysed the same broad range of outcomes we have presented; and most tended to focus on a specific risk level (low or intermediate low) rather than comparing across and within all levels of risk. Only one SR reported results for more than one outcome stratified by route subgroup. The results of these SRs were broadly in line with those we have reported.

Overall, this SR highlights that the choice between TAVI versus SAVR will undoubtedly be a highly personalised one, which in most cases will include a trade-off between an increase in the risk of certain outcomes and a decrease in the risk of others. The findings of this SR support the growing approach to enable patients to make physician-guided choices on their own care based on their personal preferences and values in the context of the Heart Team’s assessment of their inherent anatomical features, comorbidities and frailties, life expectancy and valve durability rather than the classical approach of assigning treatments simply based on estimated surgical risk.

Conclusions

Current evidence suggests that while all-cause or cardiovascular mortality may not be different for TAVI compared with SAVR, TAVI may reduce the risk of certain side effects (such as major bleeding, AKI, NOW-AF) and reduce the length of hospital stay, while SAVR may reduce the risk for other side effects (such as major vascular complications, new PPM implantation or reinterventions/rehospitalisations). Consequently, each individual patient should be engaged in a SDM framework to enable highly personalised trade-off decisions to be made based on a carefully balanced review of this evidence.

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