Review

Annular and supra-annular structure assessments for transcatheter aortic valve replacement in patients with bicuspid aortic stenosis

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The clinical use indications for transcatheter aortic valve replacement (TAVR) for the treatment of severe symptomatic aortic stenosis (AS) have expanded from patients at high surgical risk to those at low risk based on the results of multiple large-scale randomized trials. However, patients with bicuspid AS have traditionally been excluded from clinical trials due to their unfavorable morphological characteristics. Bicuspid aortic valve (BAV) is the most frequent congenital heart disease, occurring in 1% to 2% of the total population and affects more than 20% of octogenarians undergoing isolated aortic valve replacement for AS. In recent years, TAVR in patients with bicuspid AS has been the focus of research, especially with respect to the standard of prosthesis size selection. Annulus-based prosthesis size selection using computed tomography (CT) is the standard sizing strategy for tricuspid AS, but no standard sizing for bicuspid AS has been developed thus far. According to Western TAVR experiences, transcatheter heart valve (THV) size selection for BAV patients should be based on the annular structure assessment by CT measurement, whereas Chinese experiences favor adopting the supra-annulus structure assessment for THV size selection. This article will review annular and supra-annular sizing for prosthesis size selection in patients with bicuspid AS before TAVR and discuss which has more favorable clinical outcomes.

Keywords

Transcatheter aortic valve replacement (TAVR); Aortic stenosis (AS); Bicuspid aortic valve (BAV); Prosthesis size selection

1. Introduction

Transcatheter aortic valve replacement (TAVR) was first performed in 2002 under compassionate-use conditions; during follow-up, the patient's valvular function as assessed by transesophageal echocardiography (TEE) remained satisfactory over four months, and the hemodynamic profile was improved significantly. Although severe noncardiac complications occurred in the 17th week after TAVR [1], this case was a landmark event in the development of TAVR, as its conduct meant the procedure might become a better therapeutic alternative for the treatment of patients with aortic stenosis (AS) who are not surgical candidates. With the progress made toward safer vascular access, improved transcatheter valve technologies, and variable implantation techniques, TAVR for severe symptomatic AS has shown improved clinical outcomes. Though initially used only in patients who were inoperable or at high surgical risk [2, 3], clinical trials revealing the lower postprocedural complication rates of TAVR relative to those of surgical aortic valve replacement (SAVR) in intermediate- [4, 5] and low-risk patients [6–9] have since expanded clinical use indications [10]. However, major TAVR trials have excluded AS patients with bicuspid aortic valves (BAVs) [11] because of the unfavorable morphological characteristics of this condition; thus, TAVR remains a challenging procedure in such a context. First, the aortic annulus of BAV patients is more elliptical, and this, along with the enlarged anatomy of the aortic root and ascending aorta, make positioning and anchoring a transcatheter heart valve (THV) more difficult to complete [12, 13]. Second, during the process of valve deployment, the valve frame can be asymmetrically or incompletely expanded and apposed because of unequally sized leaflets and asymmetric leaflet calcification, which might result in suboptimal hemodynamic outcomes, such as increased paravalvular regurgitation (PVR) and transvalvular gradient [14–16]. Third, the risk of damage to the aortic root and ascending aorta is increased during predilatation, valve deployment, and postdilatation valvuloplasty, resulting in a greater incidence of aortic dissection [16, 17].

BAV is the most common congenital heart disease, with an estimated prevalence of 1% to 2% of the total population [18] and affects more than 20% of octogenarians undergoing isolated aortic valve replacement for AS [19, 20]. Due to the expanding indications of TAVR and the trend toward including younger and lower-risk patients [7, 21], operators are likely to encounter more BAV patients with AS going forward, especially in China [12]. Since Chinese BAV patients usually undergo valve replacement due to early onset AS and ethnic differences, the proportion of BAV morphology in severe AS patients in China receiving TAVR was 40% to 50%, which was much higher than the proportion of 1.6% to 9.3% reported among Western patients [22]. Further-

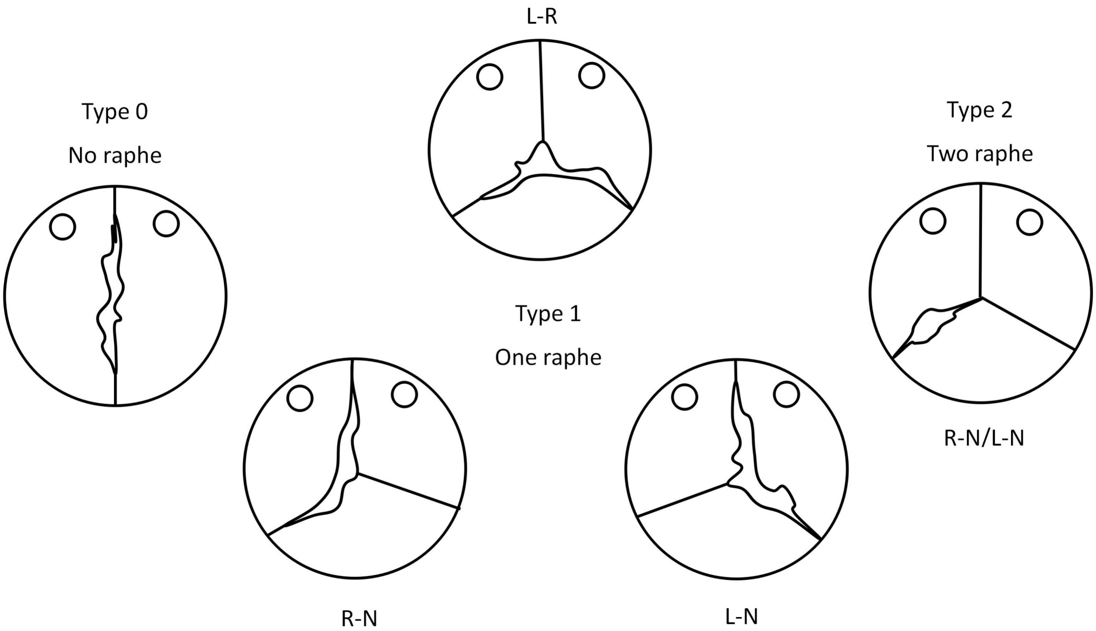

Fig. 1. Bicuspid aortic valve classification, adapted from [25]. The main category represents the number of raphes, codifying the BAVs into three types: type 0, valve with no raphe; type 1, valve with one raphe; and type 2, valve with two raphes. R, right coronary cusp; L, left coronary cusp; N, noncoronary cusp.

more, Chinese BAV patients often exhibit greater calcium volumes, leading to more challenges in performing TAVR [23]. Therefore, the importance of preprocedural planning with multimodality imaging should be emphasized.

Currently, multidetector computed tomography (CT) is a standard imaging modality for preoperative evaluation in TAVR [24]. The morphology of BAV can be seen effectively on high-resolution CT. Thus, through CT imaging, Sievers and Schmidtke [25]. Classified BAV into three major types according to the position and function of leaflets and numbers of raphae as follows: type 0 denotes BAV characterized by the presence of one commissure and two cusps, without evidence of a raphe; type 1 denotes the presence of one raphes; and type 2 denotes valve morphologies with two raphes, respectively (Fig. 1, Ref. [25]). Due to altered anatomies in BAV patients, prosthesis size selection for this population is particularly challenging. Moreover, ensuring an appropriate valve size selection is essential since undersizing can facilitate prosthesis malapposition and paravalvular leak, while oversizing may lead to annular rupture and conduction abnormality, among other complications [26, 27].

According to the latest guidelines for valvular heart disease [10], the sizing of aortic valve annulus has been regarded as the "gold standard" in prosthesis size selection, as the aortic valve annulus typically represents the tightest part of the aortic root [28, 29]. However, Xiong *et al.* [26] found that supra-annular assessment for prosthesis size selection may be a more beneficial approach to adopt for BAV patients with AS, suggesting that measuring the supra-annular aspect, which is the most constrained site, is a more appropriate method.

The present article will review the application of annular and supra-annular structure assessments for prosthesis size selection in patients with bicuspid AS before TAVR and discuss which one is more appropriate for this population.

2. Known assessments for prosthesis size selection in TAVR

Since the publication of the first expert consensus document on CT imaging before TAVR by the Society of Cardiovascular Computed Tomography (SCCT) in 2012 [30], a tremendous amount of advancement has been realized in the field. Data from many trials and remarkable technological advancements have resulted in the deep integration of CT imaging and TAVR into clinical practice, and the development of noninvasive imaging has supported the maturation of TAVR. While CT was initially adopted for the assessment of peripheral access, it is now an indispensable tool for treatment planning in the preprocedure period, especially for assessing the anatomy of the aortic valvular complex [31–33].

2.1 The annular structure assessment for BAV

Cardiac CT is considered a reference standard for the annular structure in preprocedural TAVR reports [24]. The annulus size can be measured and reported in the same fashion for BAV as for tricuspid aortic valves (TAVs). Furthermore, the degree of raphe calcification should be evaluated, as severe raphe calcification often increases the likelihood of PVR after TAVR in BAV patients [34].

The aortic annulus is defined as the luminal contour within a virtual plane aligned with the most basal attachment points of the aortic valve cusps. Quantitative assessment re-

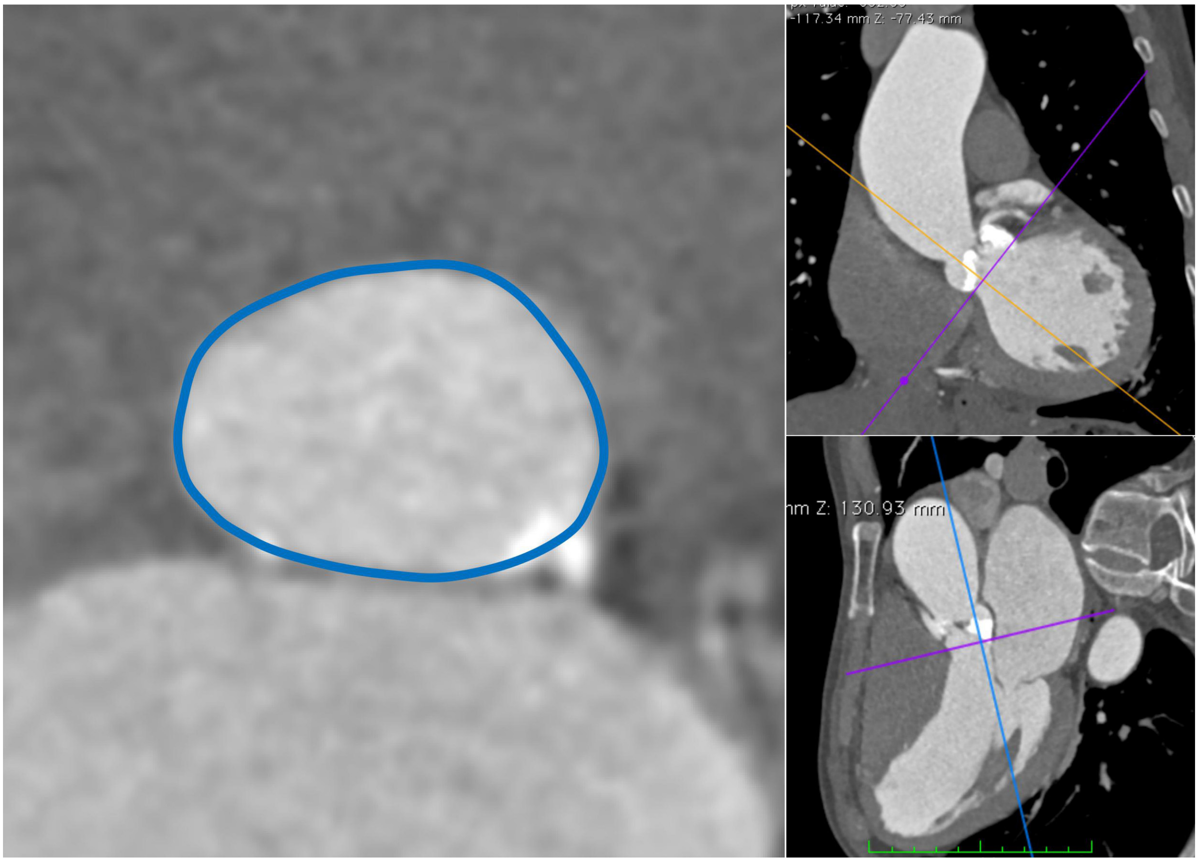

Fig. 2. Annular structure assessment based on CT measurement (note the CT images in Figs. 2,3 are from the same patient). The annular area and perimeter were measured at the insertion point of the aortic cusps (blue contour), and the position of annular plane is shown in the CT image (purple line).

quires the accurate identification of each of these points in turn to create a plane that transects all points. Defining the annulus may be a challenge for BAV, particularly for those with Sievers type 0 BAV, since there are only two hinge points to define the annular plane [35].

Measurements of the aortic annulus are performed by conducting manual, semi-automated, and automated quantifications of a single cardiac systolic phase [31, 36, 37]. In this context, calculations of the basal annular ring are collected, including aortic annular short-axis diameters, area, and perimeter, by manual or dynamic CT measurements. Details of CT measurements were previously reported [38]. Briefly, annular measurements were performed below the insertion of the aortic cusps in a double oblique short-axis view of the annulus and orthogonal to the aortic root (Fig. 2) [39]. During the standard manual measurements, the cardiac systolic phase with the largest opening of the aortic valve by visual estimation was selected as the single phase of measurement for the annulus; for dynamic automated measurements, annular measurements were gathered during any available phase throughout the cardiac cycle [39].

Almost all existing TAVR trials with prosthesis size selection by aortic valve annular measurements have reported lower all-cause mortality rates at follow-up, whether in TAV patients or in BAV patients [34, 40–42]. However, due to the special anatomical challenges presented by BAV, the conduct of TAVR in patients with bicuspid AS was associated with more frequent periprocedural complications and residual aortic regurgitation as compared with in TAV patients [14, 15], which means that the annulus perimeter–based guide of the valve size might not be suitable for application in patients with bicuspid AS with supra-annular deformity. Thus, cardiologists have suggested that prosthesis size selection in TAVR based on supra-annular structure assessment may be a more suitable approach for those patients [26].

2.2 The supra-annular structure assessment for BAV

The supra-annular level is located within the aortic root, between 4 and 8 mm above the aortic annulus (the exact distance varies from patient to patient). This level is the region where the prosthesis will be maximally constrained [26]. In Chinese TAVR centers, the narrowest portion on imaging is apparent above the annulus, using a radiographical finding known as the "waist sign". This supra-annular structure plays a key role in anchoring the THV [27].

2.2.1 Supra-annular structure assessment based on CT imaging

According to reports using CT imaging, the corresponding plane of the waist may be identified by surrounding structures, such as commissural gaps, commissural fusion, and

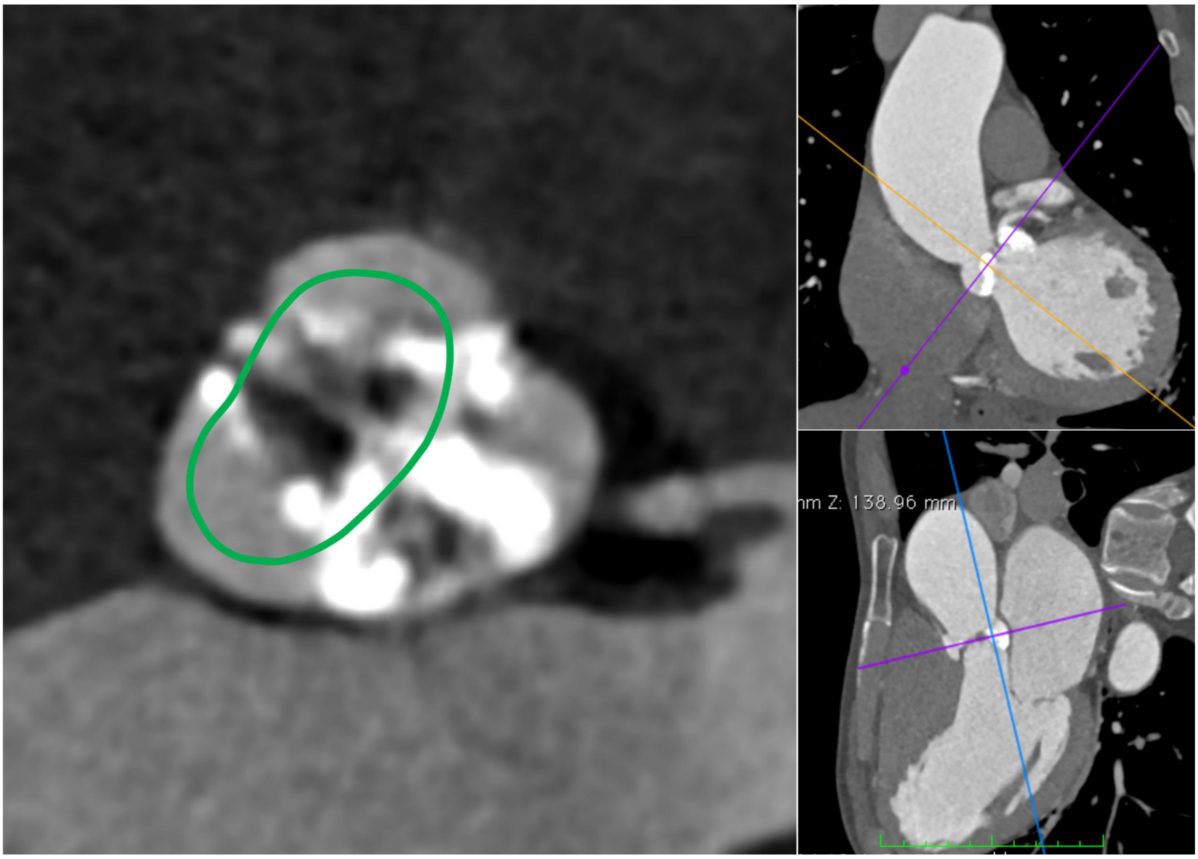

Fig. 3. Supra-annular structure assessment based on CT measurement (note the CT images in Figs. 2,3 are from the same patient). Supra-annular area and perimeter were measured at the intercommisural distance, from which a circle is defined (green contour), and the position of supra-annular plane is shown in the CT image (purple line).

calcium deposits [43]. Then, the supra-annular area and perimeter are calculated using the intercommisural distance (i.e., the distance between the innermost aspect of the two commissures [44]), from which a circle is defined (Fig. 3) [45].

Establishing supra-annular sizing based on CT measurements for prosthesis size selection is a feasible approach. Xiong *et al.* [26] demonstrated that, following supra-annular sizing in BAV patients with AS using the Lotus valve (Boston Scientific, Natick, Massachusetts, USA), the hemodynamic performance at one month of follow-up was improved significantly, with nonexistent or mild paravalvular leak. Another clinical trial reported that there was a remarkable decrease in both peak and mean gradients in BAV patients with AS who underwent TAVR by supra-annular assessment for prosthesis size selection at 30 days of follow-up, and no aortic regurgitation or stroke occurred [46]. Moreover, a clinical trial comparing the outcomes of BAV patients, whose prosthesis size selection was based on supra-annular sizing, and TAV patients, whose prosthesis size selection was based on annular sizing, revealed similar mortality and complication rates in both groups at 30 days and one year postoperatively [22].

2.2.2 Supra-annular structure assessment by sequential balloon sizing

Liu *et al.* [27] developed a strategy of sequential balloon sizing for patients with bicuspid AS to select the appropriate THV size (Fig. 4). First, the perimeter-derived diameter of the aortic annulus needs to be measured based on CT imaging before the deployment of the strategy; then, using the smallest balloon according to the minimum aortic diameter requirement for prostheses used in the procedure, the strategic implementation begins. During the process of balloon inflation, regurgitation and the “waist sign” on radiographical imaging should be checked with a simultaneous contrast injection. Sequential balloon sizing in 2-mm increments is performed until the “waist sign” occurs with less than mild regurgitation. However, if the next size of the balloon is larger than the annulus, then measurement should be stopped and the THV size should be selected based on the annulus size. After identifying the “waist sign”, operators can calculate the average diameter instead of the perimeter-derived annulus diameter as the reference for prosthesis size selection; the equation for this is as follows: average diameter (mm) = (diameter of the final balloon + perimeter-derived diameter of the annulus based on CT)/2 [27].

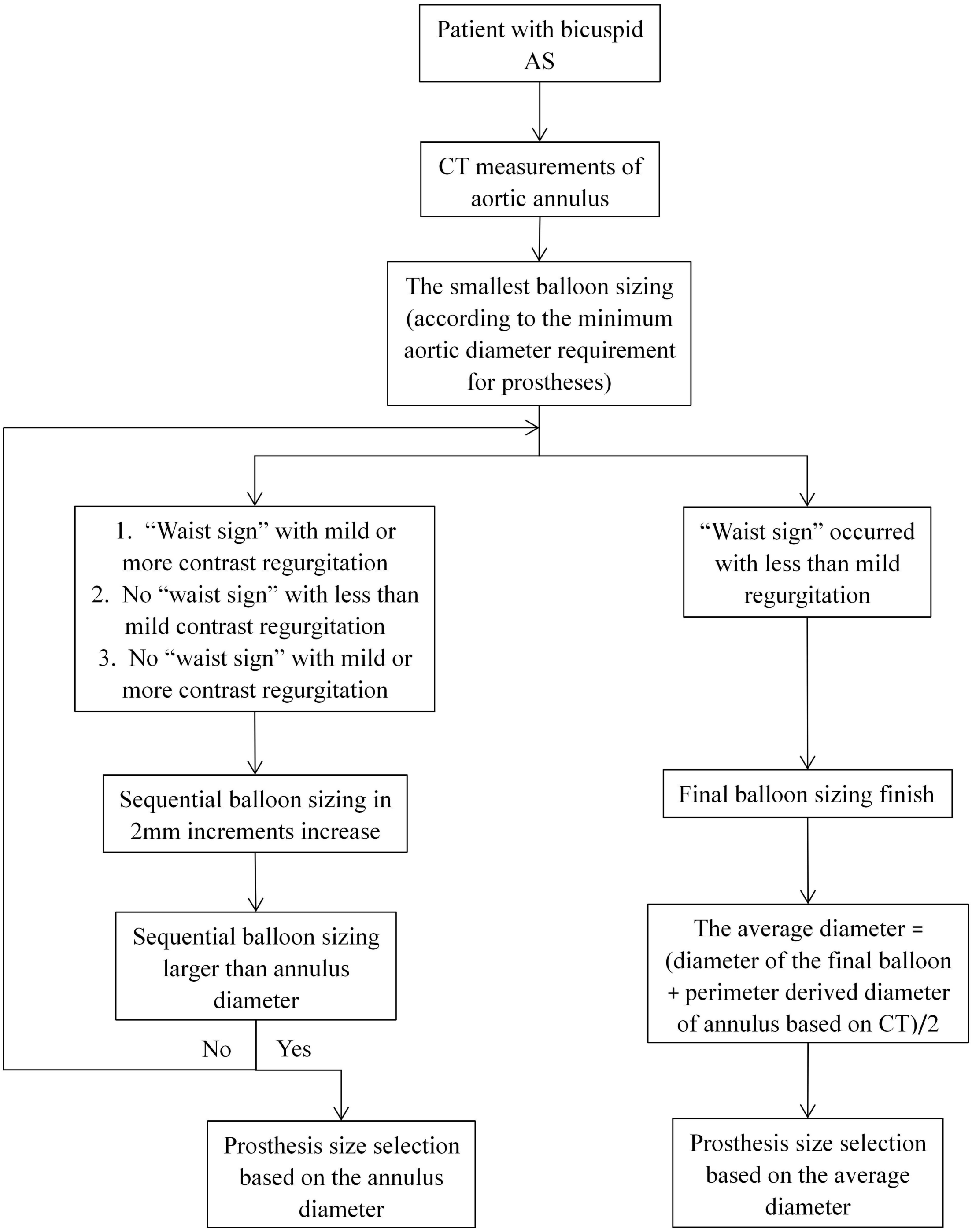

Fig. 4. Schematic illustration of prosthesis size selection based on supra-annular assessment using sequential balloon sizing. AS, aortic stenosis; CT, computed tomography.

Supra-annular structure assessments by sequential balloon sizing for THV size selection is a novel strategy from Hangzhou's experience [27]. In their clinical trial, this strategy was successfully deployed in all 12 BAV patients with AS with excellent 30 day outcomes including favorable hemodynamic profiles, 0% mortality and improved heart functional status [27].

2.2.3 Supra-annular structure assessment using the LIRA sizing method

A multicenter CT scan study detailed a supra-annular plane that predicts THV prosthesis-anchoring in raphe-type BAV (Sievers classification types 1 and 2), named as the level of implantation at the raphe (LIRA) plane [47]. The LIRA plane is regarded as the most rigid anatomical structure in the aortic root (calcific/fibrotic raphes) that might facilitate valve-anchoring during deployment. Thus, using sizing measurements taken at the LIRA plane (i.e., the LIRA sizing method) has been proposed as a viable supra-annular sizing method for selecting the prosthesis size in raphe-type BAV patients [48].

For LIRA sizing, the aortic valve virtual basal ring (VBR) first must be defined as the short-axis plane through the nadir of each coronary cusp based on CT imaging. The perimeter, area, maximal diameter, and minimal diameter of the VBR should be measured; meanwhile, the eccentricity index of the VBR stands for the circularity, calculated using the following equation: eccentricity index = 1 – (minimal diameter / maximal diameter) [49]. Then, operators may start to identify the LIRA plane. In AS patients with type 1 BAV, the prosthesis should be anchored at the level of the calcific/fibrotic raphe along the aortic root; accordingly, the LIRA plane may be identified as the area that cuts the raphe at its maximum protrusion along the aortic root. In AS patients with type 2 BAV, due to their BAV anatomy including two raphes, the prosthesis should be anchored at the level of the larger raphe with the greater amount of calcium; hence, in these patients, the LIRA plane is identified as the portion that cuts the major raphe at its maximum protrusion along the aortic root [47]. Finally, THV size is selected according to the VBR and LIRA plane perimeters. If a discrepancy is found in measurements between the VBR and the LIRA plane, then prosthesis sizing should be based on the plane with the smallest perimeter; conversely, if a concordance is found, then prosthesis sizing should be based on the VBR (Fig. 5). Briefly, the LIRA plane sizing method could be adopted when there is a discrepancy between the LIRA plane and annular plane measurements (i.e., when the LIRA plane perimeter is smaller than the VBR plane), leading to the selection of smaller prostheses. Detailed CT images of prosthesis sizing according to the LIRA method are included in a previous report [48].

Iannopollo *et al.* [48] evaluated the short-term outcomes and safety of the LIRA sizing method in AS patients with raphe-type BAV; ultimately, the device success rate was 100%, in-hospital outcomes showed that the mean prosthesis gradient predischarge was 8.2 ± 2.9 mmHg without moderate-to-severe paravalvular leak, and no mean gradient value was higher than 20 mmHg. Additionally, no instance of permanent pacemaker implantation occurred. These authors surmised that the LIRA sizing method was feasible and may be a better strategy to optimize THV prosthesis sizing in patients with raphe-type bicuspid AS [48]. However, further larger clinical trials are required to confirm their findings.

3. Discussion

The unique morphological characteristics of BAV increase the risk of valve malapposition, paravalvular leak, annulus rupture, and aortic dissection during TAVR procedures [12]. Hence, early clinical trials of TAVR and relative guidelines regarded the existence of BAV with AS a relative contraindication [2, 50]. In recent years, however, major medical centers around the world have paid increasing attention to BAV patients with AS and conducted BAV-related trials, although there is still a paucity of data on TAVR outcomes in BAV patients and no consensus among experts on the treatment of this disease between China and Western countries.

Since 2010, more than 4500 TAVR procedures had been performed in China [22], mostly concentrated in Beijing, Shanghai, Hangzhou, Nanchang, and other developed regions with high-quality medical resources. There is an unexpectedly high frequency of BAV morphology with an enormous aortic valve calcium burden in Chinese AS patients, which is different from the profile of Western patients undergoing TAVR [23]. This revelation has influenced clinical trials of Chinese TAVR, with a fundamental change in the protocol to include the assessment approach for prosthesis size selection.

Annulus-based prosthesis size selection from CT measurements is the standard sizing strategy for tricuspid AS; however, no standard sizing for bicuspid AS has been developed so far. Large clinical trials in Western countries, which have evaluated the outcomes of TAVR in BAV patients with AS, still adopt the annulus structure assessment for THV size selection [34, 42, 51], while the TAVR clinical experience in China has advocated for using the supra-annular structure assessment for THV size selection in this population. Post-TAVR imaging has proven the rationality of the latter approach and shows that the prosthesis is most constrained at the site of the valve orifice rather than the annulus in BAV [43].

A retrospective single-center analysis comparing annular versus supra-annular sizing for TAVR in BAV patients with AS demonstrated that supra-annular sizing using CT measurement differed from annulus-based sizing in 38.7% of patients, with increased and reduced sizing in 19.8% and 17.5% of patients, respectively [44]. The findings suggest a high rate of increased sizing was incurred by supra-annular sizing, which is a concern given the known association of valve oversizing and subsequent annular rupture [52]. Additionally, the concept that supra-annular sizing impacts potential valve size is consistent with the work by Weir-McCall *et al.* [45], who reported that THV sizing based on supra-annular measurement was significantly larger than that based on annular measurement, even though clinical and valve-related events were not elevated in BAV patients with AS who underwent TAVR by supra-annular sizing relative to those who underwent TAVR by annular sizing. Therefore, according to the results of the only two clinical trials comparing annular versus supra-annular sizing for TAVR in BAV disease, the study groups for the two trials reached a consensus that annular sizing for TAVR in BAV is safe and feasible, while the role of supra-annular sizing is questionable [44, 45]. Moreover, some researchers have suggested that, when the supra-annular size is smaller, that supra-annular sizing can be used for sizing the valve, while the annulus sizing method should be used in patients in whom the supra-annular size is equal or greater than the annulus size [51].

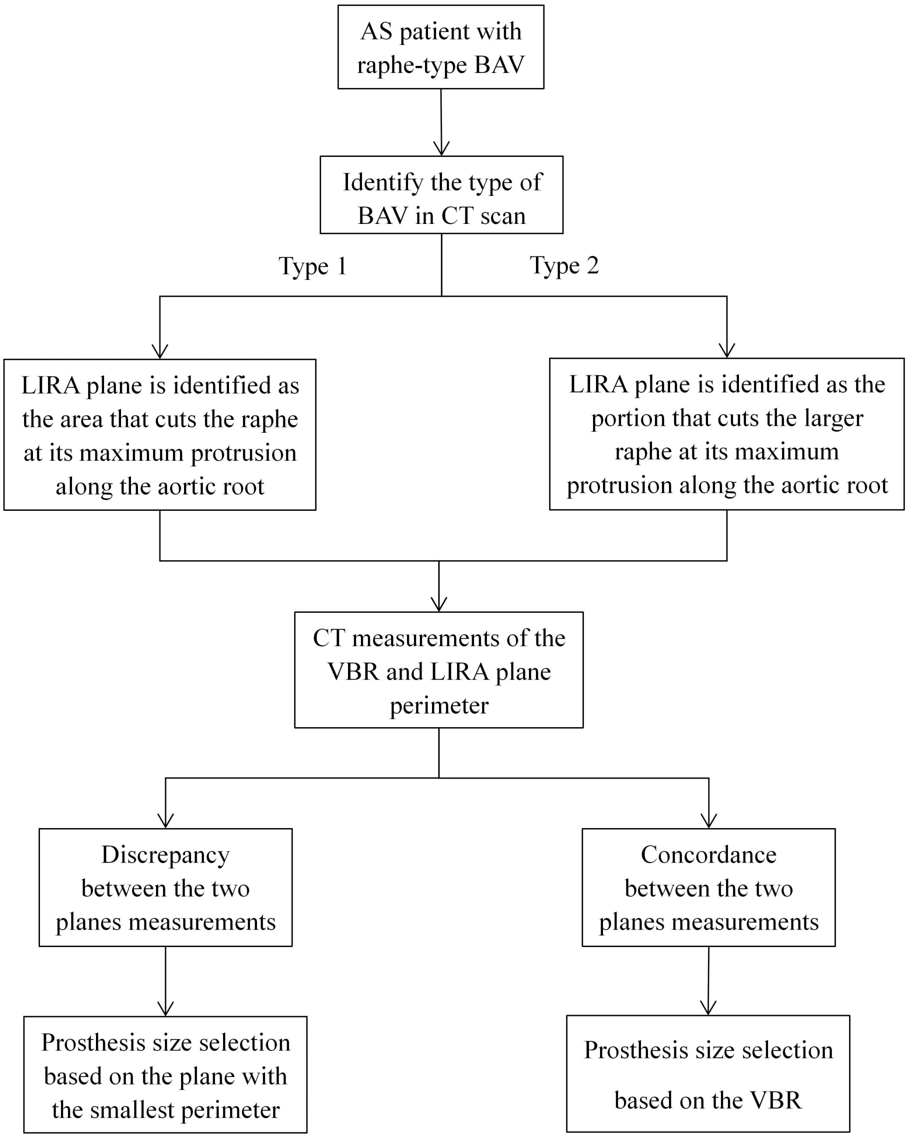

Fig. 5. Schematic illustration of prosthesis size selection based on supra-annular assessment using the LIRA sizing method. AS, aortic stenosis; BAV, bicuspid aortic valve; CT, computed tomography, LIRA, level of implantation at the raphe; VBR, virtual basal ring.

Although the above two Western TAVR trials comparing annular versus supra-annular sizing reached similar conclusions, they included small subgroups of BAV patients undergoing a workup for TAVR, and further large multicenter trials will be needed to verify their conclusions. Moreover, we hypothesize that similar TAVR trials would have different results if based off a Chinese population/cohort since there is an excess of severe aortic valve calcification in Chinese patients with bicuspid AS relative to among Western patients [23], that is, their narrower supra-annular structures provide greater resistance to valve expansion than the annulus (Fig. 3). As such, THV size selection by supra-annular sizing might be more appropriate for these Chinese patients. Comparative studies between annular and supra-annular sizing are lacking currently and should be the focus of future research efforts.

In addition to the retrospective analysis comparing clinical outcomes between annular and supra-annular sizing, prospective studies are also important. Several studies have conducted preprocedural simulation by combining three-dimensional (3D) printing technology with a pressure sensor system to accurately analyze the causes of paravalvular leak caused by the presence of an irregular annulus and calcification of the device landing zone, and the results were consistent with prior TAVR outcomes [53–55]. Thus, the preprocedural simulation for *in vitro* TAVR using 3D printed tissue–mimicking phantoms may be performed to assist the formulation of an operational plan, THV size selection, and valve deployment in patients with bicuspid AS. For instance, operators might choose different prosthesis sizes for *in vitro* TAVR according to annular or supra-annular sizing based on CT measurements, then quantitatively predict the hemodynamic results to decide the optimal prosthesis size. Although 3D printing is expensive and time-consuming (especially when implanting different sizes of prostheses), it offers unique opportunities to tailor surgical procedures to patients through the creation of physical models of the patient anatomy derived from routine preprocedural imaging studies [56]. Furthermore, 3D printing has expanded beyond just the visualization of anatomy; it has been shown to decrease the learning curve for difficult procedures and improve preprocedural planning for cases involving complex 3D anatomies [57]. Perhaps such preprocedural simulation might also help to increase the procedural success rate and decrease periprocedural complication rate. Further TAVR trials will be needed to prove the value of the preprocedural simulation with 3D printing technology.

4. Conclusions

Although multiple series have demonstrated TAVR to be reasonably safe and efficacious in the BAV population, a higher rate of postprocedural complications was seen in those patients as compared with TAV patients due to the special morphological characteristics of BAV. Therefore, appropriate prosthesis size selection is essential. Currently, some studies have proven that both annular and supra-annular structure assessments for prosthesis size selection in bicuspid AS are feasible, but there remain few comparative studies about annular versus supra-annular sizing and no consensus among experts on the standard sizing strategy for bicuspid AS. Further studies will be required to explore the optimal strategy of THV size selection.

Author contributions

YQW, RG and JDL developed the research question. JDL performed the literature review, and drafted the manuscript. RG, XDL and ZPZ contributed to the literature review and data collection. YQW and JDL critically reviewed the manuscript and revised it for any scientific and technical errors. All authors read and approved the final manuscript.

Ethics approval and consent to participate

All patients give consent for publication.

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Conflict of interest

The authors declare no conflict of interest.

References

[1] Cribier A, Eltchaninoff H, Bash A, Borenstein N, Tron C, Bauer F, *et al.* Percutaneous Transcatheter Implantation of an Aortic Valve Prosthesis for Calcific Aortic Stenosis: first human case description. Circulation. 2002; 106: 3006–3008.

[2] Smith CR, Leon MB, Mack MJ, Miller DC, Moses JW, Svensson LG, *et al.* Transcatheter versus surgical aortic-valve replacement in high-risk patients. The New England Journal of Medicine. 2011; 364: 2187–2198.

[3] Leon MB, Smith CR, Mack M, Miller DC, Moses JW, Svensson LG, *et al.* Transcatheter Aortic-Valve Implantation for Aortic Stenosis in Patients who cannot Undergo Surgery. New England Journal of Medicine. 2010; 363: 1597–1607.

[4] Leon MB, Smith CR, Mack MJ, Makkar RR, Svensson LG, Kodali SK, *et al.* Transcatheter or Surgical Aortic-Valve Replacement in Intermediate-Risk Patients. The New England Journal of Medicine. 2016; 374: 1609–1620.

[5] Thourani VH, Kodali S, Makkar RR, Herrmann HC, Williams M, Babaliaros V, *et al.* Transcatheter aortic valve replacement versus surgical valve replacement in intermediate-risk patients: a propensity score analysis. Lancet. 2016; 387: 2218–2225.

[6] Mack MJ, Leon MB, Thourani VH, Makkar R, Kodali SK, Russo M, *et al.* Transcatheter Aortic-Valve Replacement with a Balloon-Expandable Valve in Low-Risk Patients. The New England Journal of Medicine. 2019; 380: 1695–1705.

[7] Hofer F, Hengstenberg C, Goliasch G, Grygier M, Mascherbauer J, Siller-Matula JM. Transcatheter versus surgical aortic valve replacement in low-risk patients: a meta-analysis of randomized trials. Clinical Research in Cardiology. 2020; 109: 761–775.

[8] Waksman R, Craig PE, Torguson R, Asch FM, Weissman G, Ruiz D, *et al.* Transcatheter Aortic Valve Replacement in Low-Risk Patients with Symptomatic Severe Bicuspid Aortic Valve Stenosis. JACC: Cardiovascular Interventions. 2020; 13: 1019–1027.

[9] Braghiroli J, Kapoor K, Thielhelm TP, Ferreira T, Cohen MG. Transcatheter aortic valve replacement in low risk patients: a review of PARTNER 3 and Evolut low risk trials. Cardiovascular Diagnosis and Therapy. 2020; 10: 59–71.

[10] Otto CM, Nishimura RA, Bonow RO, Carabello BA, Erwin JP, Gentile F, *et al.* 2020 ACC/AHA Guideline for the Management of Patients with Valvular Heart Disease: Executive Summary: a Report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. Circulation. 2021; 143: e35–e71.

[11] Adams DH, Popma JJ, Reardon MJ, Yakubov SJ, Coselli JS, Deeb GM, *et al.* Transcatheter aortic-valve replacement with a self-expanding prosthesis. The New England Journal of Medicine. 2014; 370: 1790–1798.

[12] Zhao Z, Jilaihawi H, Feng Y, Chen M. Transcatheter aortic valve implantation in bicuspid anatomy. Nature Reviews Cardiology. 2015; 12: 123–128.

[13] Patel A, Leon MB. Transcatheter aortic valve replacement in patients with bicuspid aortic valves. Journal of Thoracic Disease. 2018; 10: S3568–S3572.

[14] Bauer T, Linke A, Sievert H, Kahlert P, Hambrecht R, Nickenig G, *et al.* Comparison of the effectiveness of transcatheter aortic valve implantation in patients with stenotic bicuspid versus tricuspid aortic valves (from the German TAVI Registry). The American Journal of Cardiology. 2014; 113: 518–521.

[15] Mylotte D, Lefevre T, Søndergaard L, Watanabe Y, Modine T, Dvir D, *et al.* Transcatheter aortic valve replacement in bicuspid aortic valve disease. Journal of the American College of Cardiology. 2014; 64: 2330–2339.

[16] Praz F, Windecker S, Huber C, Carrel T, Wenaweser P. Expanding Indications of Transcatheter Heart Valve Interventions. JACC: Cardiovascular Interventions. 2015; 8: 1777–1796.

[17] Al-Attar N, Himbert D, Barbier F, Vahanian A, Nataf P. Delayed aortic dissection after transcatheter aortic valve implantation. The Journal of Heart Valve Disease. 2013; 22: 701–703.

[18] Vincent F, Ternacle J, Denimal T, Shen M, Redfors B, Delhaye C, *et al.* Transcatheter Aortic Valve Replacement in Bicuspid Aortic Valve Stenosis. Circulation. 2021; 143: 1043–1061.

[19] Roberts WC, Ko JM. Frequency by decades of unicuspid, bicuspid, and tricuspid aortic valves in adults having isolated aortic valve

replacement for aortic stenosis, with or without associated aortic regurgitation. Circulation. 2005; 111: 920–925.
[20] Roberts WC, Janning KG, Ko JM, Filardo G, Matter GJ. Frequency of congenitally bicuspid aortic valves in patients ≥80 years of age undergoing aortic valve replacement for aortic stenosis (with or without aortic regurgitation) and implications for transcatheter aortic valve implantation. The American Journal of Cardiology. 2012; 109: 1632–1636.
[21] Popma JJ, Deeb GM, Yakubov SJ, Mumtaz M, Gada H, O'Hair D, *et al.* Transcatheter Aortic-Valve Replacement with a Self-Expanding Valve in Low-Risk Patients. New England Journal of Medicine. 2019; 380: 1706–1715.
[22] Fu B, Chen Q, Zhao F, Guo Z, Jiang N, Wang X, *et al.* Efficacy and safety of transcatheter aortic valve implantation in patients with severe bicuspid aortic stenosis. Annals of Translational Medicine. 2020; 8: 873–873.
[23] Jilaihawi H, Wu Y, Yang Y, Xu L, Chen M, Wang J, *et al.* Morphological characteristics of severe aortic stenosis in China: imaging corelab observations from the first Chinese transcatheter aortic valve trial. Catheterization and Cardiovascular Interventions. 2015; 85: 752–761.
[24] Jilaihawi H, Kashif M, Fontana G, Furugen A, Shiota T, Friede G, *et al.* Cross-Sectional Computed Tomographic Assessment Improves Accuracy of Aortic Annular Sizing for Transcatheter Aortic Valve Replacement and Reduces the Incidence of Paravalvular Aortic Regurgitation. Journal of the American College of Cardiology. 2012; 59: 1275–1286.
[25] Sievers H, Schmidtke C. A classification system for the bicuspid aortic valve from 304 surgical specimens. The Journal of Thoracic and Cardiovascular Surgery. 2007; 133: 1226–1233.
[26] Xiong T, Feng Y, Li Y, Zhao Z, Liao Y, Ou Y, *et al.* Supra-Annular Sizing for Transcatheter Aortic Valve Replacement Candidates with Bicuspid Aortic Valve. JACC: Cardiovascular Interventions. 2018; 11: 1789–1790.
[27] Liu X, He Y, Zhu Q, Gao F, He W, Yu L, *et al.* Supra-annular structure assessment for self-expanding transcatheter heart valve size selection in patients with bicuspid aortic valve. Catheterization and Cardiovascular Interventions. 2018; 91: 986–994.
[28] Piazza N, de Jaegere P, Schultz C, Becker AE, Serruys PW, Anderson RH. Anatomy of the aortic valvar complex and its implications for transcatheter implantation of the aortic valve. Circulation: Cardiovascular Interventions. 2008; 1: 74–81.
[29] Kasel AM, Cassese S, Bleiziffer S, Amaki M, Hahn RT, Kastrati A, *et al.* Standardized imaging for aortic annular sizing: implications for transcatheter valve selection. JACC: Cardiovascular Imaging. 2013; 6: 249–262.
[30] Achenbach S, Delgado V, Hausleiter J, Schoenhagen P, Min JK, Leipsic JA. SCCT expert consensus document on computed tomography imaging before transcatheter aortic valve implantation (TAVI)/transcatheter aortic valve replacement (TAVR). Journal of Cardiovascular Computed Tomography. 2012; 6: 366–380.
[31] Binder RK, Webb JG, Willson AB, Urena M, Hansson NC, Norgaard BL, *et al.* The impact of integration of a multidetector computed tomography annulus area sizing algorithm on outcomes of transcatheter aortic valve replacement: a prospective, multicenter, controlled trial. Journal of the American College of Cardiology. 2013; 62: 431–438.
[32] Foldyna B, Jungert C, Luecke C, von Aspern K, Boehmer-Lasthaus S, Rueth EM, *et al.* CT evaluation prior to transapical aortic valve replacement: semi-automatic versus manual image segmentation. The International Journal of Cardiovascular Imaging. 2015; 31: 1233–1242.
[33] Baeßler B, Mauri V, Bunck AC, Pinto Dos Santos D, Friedrichs K, Maintz D, *et al.* Software-automated multidetector computed tomography-based prosthesis-sizing in transcatheter aortic valve replacement: Inter-vendor comparison and relation to patient outcome. International Journal of Cardiology. 2018; 272: 267–272.
[34] Yoon S, Bleiziffer S, De Backer O, Delgado V, Arai T, Ziegelmueller J, *et al.* Outcomes in Transcatheter Aortic Valve Replacement for Bicuspid Versus Tricuspid Aortic Valve Stenosis. Journal of the American College of Cardiology. 2017; 69: 2579–2589.
[35] Michelena HI, Prakash SK, Della Corte A, Bissell MM, Anavekar N, Mathieu P, *et al.* Bicuspid aortic valve: identifying knowledge gaps and rising to the challenge from the International Bicuspid Aortic Valve Consortium (BAVCon). Circulation. 2014; 129: 2691–2704.
[36] Blanke P, Spira EM, Ionasec R, Meinel FG, Ebersberger U, Scheuering M, *et al.* Semiautomated quantification of aortic annulus dimensions on cardiac CT for TAVR. JACC: Cardiovascular Imaging. 2014; 7: 320–322.
[37] Lou J, Obuchowski NA, Krishnaswamy A, Popovic Z, Flamm SD, Kapadia SR, *et al.* Manual, semiautomated, and fully automated measurement of the aortic annulus for planning of transcatheter aortic valve replacement (TAVR/TAVI): analysis of interchangeability. Journal of Cardiovascular Computed Tomography. 2015; 9: 42–49.
[38] Truong QA, Legasto AC, Deaño RC, Bachman DP, Bhatt D, Al'Aref SJ, *et al.* Performance of Dynamic Automated CT Annular Measurements Compared to Standard Manual Measurements for Transcatheter Aortic Valve Replacement Sizing. Radiology. Cardiothoracic Imaging. 2019; 1: e180025.
[39] Blanke P, Weir-McCall JR, Achenbach S, Delgado V, Hausleiter J, Jilaihawi H, *et al.* Computed tomography imaging in the context of transcatheter aortic valve implantation (TAVI) / transcatheter aortic valve replacement (TAVR): an expert consensus document of the Society of Cardiovascular Computed Tomography. Journal of Cardiovascular Computed Tomography. 2019; 13: 1–20.
[40] Liao Y, Li Y, Xiong T, Ou Y, Lv W, He J, *et al.* Comparison of procedural, clinical and valve performance results of transcatheter aortic valve replacement in patients with bicuspid versus tricuspid aortic stenosis. International Journal of Cardiology. 2018; 254: 69–74.
[41] Forrest JK, Kaple RK, Ramlawi B, Gleason TG, Meduri CU, Yakubov SJ, *et al.* Transcatheter Aortic Valve Replacement in Bicuspid Versus Tricuspid Aortic Valves from the STS/ACC TVT Registry. JACC: Cardiovascular Interventions. 2020; 13: 1749–1759.
[42] Sannino A, Cedars A, Stoler RC, Szerlip M, Mack MJ, Grayburn PA. Comparison of Efficacy and Safety of Transcatheter Aortic Valve Implantation in Patients with Bicuspid Versus Tricuspid Aortic Valves. The American Journal of Cardiology. 2017; 120: 1601–1606.
[43] Xiong T, Li Y, Feng Y, Liao Y, Zhao Z, Mylotte D, *et al.* Understanding the Interaction between Transcatheter Aortic Valve Prostheses and Supra-Annular Structures from Post-Implant Stent Geometry. JACC: Cardiovascular Interventions. 2019; 12: 1164–1171.
[44] Kim W, Renker M, Rolf A, Fischer-Rasokat U, Wiedemeyer J, Doss M, *et al.* Annular versus supra-annular sizing for TAVI in bicuspid aortic valve stenosis. EuroIntervention. 2019; 15: e231–e238.
[45] Weir-McCall JR, Attinger-Toller A, Blanke P, Perlman GY, Sellers SL, Wood D, *et al.* Annular versus supra-annular sizing for transcatheter aortic valve replacement in bicuspid aortic valve disease. Journal of Cardiovascular Computed Tomography. 2020; 14: 407–413.
[46] Jeger R, Reuthebuch O, Fahrni G, Laborde J, Vogel R, Kaiser C. Supra-annular sizing for transcatheter valve implantation in bicuspid aortic stenosis. Postepy W Kardiologii Interwencyjnej. 2018; 14: 187–190.
[47] Iannopollo G, Romano V, Buzzatti N, De Backer O, Søndergaard L, Merkely B, *et al.* A novel supra-annular plane to predict TAVI prosthesis anchoring in raphe-type bicuspid aortic valve disease: the LIRA plane. EuroIntervention. 2020; 16: 259–261.
[48] Iannopollo G, Romano V, Buzzatti N, Ancona M, Ferri L, Russo F, *et al.* Supra-annular sizing of transcatheter aortic valve prostheses in raphe-type bicuspid aortic valve disease: the LIRA method.

International Journal of Cardiology. 2020; 317: 144–151.
[49] Wong DT, Bertaso AG, Liew GY, Thomson VS, Cunnington MS, Richardson JD, *et al*. Relationship of aortic annular eccentricity and paravalvular regurgitation post transcatheter aortic valve implantation with CoreValve. The Journal of Invasive Cardiology. 2013; 25: 190–195.
[50] Vahanian A, Alfieri O, Andreotti F, Antunes MJ, Barón-Esquivias G, Baumgartner H, *et al*. Guidelines on the management of valvular heart disease (version 2012): the Joint Task Force on the Management of Valvular Heart Disease of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS). European Journal of Cardio-Thoracic Surgery. 2012; 42: S1–S44.
[51] Tchetche D, de Biase C, van Gils L, Parma R, Ochala A, Lefevre T, *et al*. Bicuspid Aortic Valve Anatomy and Relationship with Devices: the BAVARD Multicenter Registry. Circulation: Cardiovascular Interventions. 2019; 12: e7107.
[52] Barbanti M, Yang T, Rodès Cabau J, Tamburino C, Wood DA, Jilaihawi H, *et al*. Anatomical and procedural features associated with aortic root rupture during balloon-expandable transcatheter aortic valve replacement. Circulation. 2013; 128: 244–253.
[53] Qian Z, Wang K, Liu S, Zhou X, Rajagopal V, Meduri C, *et al*. Quantitative Prediction of Paravalvular Leak in Transcatheter Aortic Valve Replacement Based on Tissue-Mimicking 3D Printing. JACC: Cardiovascular Imaging. 2017; 10: 719–731.
[54] Tanaka Y, Saito S, Sasuga S, Takahashi A, Aoyama Y, Obama K, *et al*. Quantitative assessment of paravalvular leakage after transcatheter aortic valve replacement using a patient-specific pulsatile flow model. International Journal of Cardiology. 2018; 258: 313–320.
[55] Hosny A, Dilley JD, Kelil T, Mathur M, Dean MN, Weaver JC, *et al*. Pre-procedural fit-testing of TAVR valves using parametric modeling and 3D printing. Journal of Cardiovascular Computed Tomography. 2019; 13: 21–30.
[56] Luo H, Meyer-Szary J, Wang Z, Sabiniewicz R, Liu Y. Three-dimensional printing in cardiology: Current applications and future challenges. Cardiology Journal. 2017; 24: 436–444.
[57] Hermsen JL, Burke TM, Seslar SP, Owens DS, Ripley BA, Mokadam NA, e*t al*. Scan, plan, print, practice, perform: Development and use of a patient-specific 3-dimensional printed model in adult cardiac surgery. The Journal of Thoracic and Cardiovascular Surgery. 2017; 153: 132–140.