Cardiovasc Surg Int 2024;11(3):193-201
http://dx.doi.org/DOI: 10.5606/e-cvsi.2024.1647
www.e-cvsi.org

Cardiovascular Surgery and Interventions

Original Article Open Access

Aortic angle in predicting aortic regurgitation after transcatheter aortic valve implantation

Tolga Onuk, Fuat Polat, Barış Yaylak

Department of Cardiology, Dr. Siyami Ersek Thoracic and Cardiovascular Surgery Training and Research Hospital, İstanbul, Türkiye

Received: March 05, 2024 ***Accepted:*** September 16, 2024 ***Published online:*** October 17, 2024

ABSTRACT

Objectives: The primary aim of the study was to evaluate the effect of the aortic angle on aortic regurgitation after transcatheter aortic valve implantation (TAVI), while secondary objectives involved exploring correlations between the aortic angle and various clinical and demographic factors.

Patients and methods: The single-center observational study included 105 patients (55 females, 50 males; mean age: 78.8±6.7 years; range, 70 to 92 years) who underwent TAVI between October 2019 and September 2023. Comprehensive preprocedural evaluations were conducted, including echocardiography and computed tomography. Evolut R self-expandable supra-annular valves were used in the procedures.

Results: Hypertension (85.7%) and atrial fibrillation (78.2%) were the most common comorbidities, and 14.3% of patients exhibited moderate aortic regurgitation before TAVI. The mean aortic angle was 46.8±10.6° before the procedure. In receiver operating characteristic analysis, the aortic angle affecting aortic regurgitation after TAVI was determined as 49.5°. After TAVI, significant reductions in pulmonary artery pressures and aortic regurgitation prevalence were observed. Aortic regurgitation decreased in 38.1% of patients, remained unchanged in 47.6% of patients, and increased in 14.3% of patients. A weak linear relationship (R^2=0.011) was observed between aortic insufficiency and the aortic angle.

Conclusion: The study showed that an aortic angle of 49.5° can be used to predict aortic regurgitation after TAVI. However, a weak linear correlation was detected between the aortic angle and aortic regurgitation.

Keywords: Aortic angle, aortic valve insufficiency, computed tomography, echocardiography, transcatheter aortic valve replacement.

Aortic stenosis (AS) refers to the narrowing of the aortic valve opening, restricting blood flow from the left ventricle to the aorta. This condition impedes efficient blood circulation and imposes pressure on the heart, potentially leading to symptoms such as chest pain, shortness of breath, and, ultimately, heart failure.[1,2] The most common cause of AS is progressive calcification and stiffening of the valve leaflets, predominantly affecting older individuals.[3]

Epidemiologically, AS represents a prevalent valvular heart disease, particularly in aging populations. Its prevalence escalates with age, and it is estimated that around 2 to 9% of individuals over 65 years exhibit some degree of AS.[4-6] As life expectancy rises, AS incidence is expected to surge, necessitating effective treatment strategies.[7]

Transcatheter aortic valve implantation (TAVI) involves inserting a prosthetic valve via catheter-based techniques, often through the femoral artery, and positioning it within the native aortic valve. This minimally invasive procedure allows for shorter recovery times and reduced complications.[8] Transcatheter aortic valve implantation utilization has increased due to technological advancements and acceptance as a viable AS treatment.[9,10]

Corresponding author: Tolga Onuk, MD. Dr. Siyami Ersek Göğüs Kalp ve Damar Cerrahisi Eğitim ve Araştırma Hastanesi, Kardiyoloji Kliniği, 34668 Üsküdar, İstanbul, Türkiye.
E-mail: tolgaonuk77@gmail.com

Citation:
Onuk T, Polat F, Yaylak B. Aortic angle in predicting aortic regurgitation after transcatheter aortic valve implantation. Cardiovasc Surg Int 2024;11(3):193-201. doi: 10.5606/e-cvsi.2024.1647.

While TAVI has revolutionized AS management, complications include vascular issues, bleeding, stroke, conduction abnormalities, and aortic regurgitation (AR).[11,12] Factors influencing AR after TAVI include anatomical considerations, valve sizing, and procedural techniques.[13,14] Moderate to severe AR can lead to heart failure and increased morbidity.[15]

Research into aortic valve anatomy and its impact on TAVI outcomes is evolving, with studies exploring aortic annulus dimensions, calcification, and angles.[16] The aortic angle, measured by computed tomography, refers to the angle between the horizontal and aortic annular planes in the coronal section. A greater angle may indicate higher risk for complications.[17,18]

This study aimed to investigate the correlation between the aortic angle and AR following TAVI in patients without advanced annular calcification, using self-expandable supra-annular valves, and offer insights into a specific TAVI subset, potentially refining prognostic information for this cohort.

PATIENTS AND METHODS

This observational study was conducted with 105 patients (55 females, 50 males; mean age: 78.8±6.7 years; range, 70 to 92 years) who underwent TAVI at the Dr. Siyami Ersek Thoracic and Cardiovascular Surgery Training and Research Hospital between October 2019 and September 2023. Patients with symptomatic severe AS were presented to a TAVI council consisting of cardiologists and cardiovascular surgeons. According to the council's decision, patients who were recommended TAVI and underwent the procedure in the same hospital were included in the study. The inclusion criteria were established as nonemergency TAVI and the presence of complete preprocedure, postprocedure, and predischarge data. The exclusion criteria encompassed active malignancy, bleeding disorders, selection of an entry site other than transfemoral, patients with bicuspid aortic valves, advanced annular calcification, and severe aortic insufficiency. The study protocol was approved by the İstanbul Yeni Yüzyıl University Ethics Committee (decision date: 04.03.2024, no: 2024/03-1234). Written informed consent was acquired from all participants. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Demographic data, comorbidities, and baseline characteristics were collected from electronic medical records. Preprocedural evaluations encompassed echocardiography, computed tomography, and the documentation of various cardiac parameters and anatomical measurements. All TAVI procedures were performed by experienced interventional cardiologists using the Medtronic Evolut R system self-expandable supra-annular valve (Medtronic, Minneapolis, MN, USA) Valve sizing (26, 29, or 34 mm) was determined based on individual patient anatomy. Pre- and postdilatation techniques were applied as clinically indicated.

Patients underwent meticulous predischarge assessments, including echocardiography and measurement of cardiac parameters. Follow-up evaluations aimed to compare pre-TAVI and post-TAVI values, assessing changes in left ventricular function, aortic gradients, pulmonary artery pressures, and the presence of aortic insufficiency.

The primary outcome was the impact of the aortic angle on AR. Secondary outcomes were the exploration of clinical and demographic factors that may influence variations in the aortic angle.

Statistical analysis

Statistical analysis was performed using IBM SPSS version 25.0 software (IBM Corp., Armonk, NY, USA). Descriptive statistics were used to summarize patient characteristics and baseline measurements. Continuous variables were presented as mean ± standard deviation (SD) or median with interquartile range (IQR). Paired t-tests or nonparametric tests were utilized to compare pre- and postprocedural values. Spearman correlation analyses were conducted to explore associations between variables. Receiver operating characteristic (ROC) analysis was employed to determine cutoff values for aortic angles affecting AR. A p-value <0.05 was considered statistically significant.

RESULTS

The prevalent comorbidities identified were hypertension (85.7%) and atrial fibrillation (75.2%). Concomitant coronary artery disease was present in 71.4% of the patient population. The median EuroSCORE II value for these patients was 4.2 (IQR, 3.2-4.8).

In the preprocedural echocardiographic assessments, the mean left ventricular ejection fraction (EF) was 48.1±14.1, the mean systolic pulmonary

Table 1
Clinical and demographic characteristics

	n	%	Mean±SD	IQR	25th-75th Percentiles
Patient characteristics					
Age (year)			78.8±6.7		
Sex					
Male	50	47.6			
Body mass index (kg/m²)			28.2±5.1		
Dyslipidemia (%)	50	47.6			
Diabetes mellitus (%)	45	42.9			
Hypertension (%)	90	85.7			
Atrial fibrillation (%)	79	75.2			
History of CAD (%)	75	71.4			
EuroSCORE II				4.2	3.2-4.8
Echocardiographic measurements					
Left ventricular ejection fraction (%)			48.1±14.1		
Interventricular septum thickness (mm)			13.8±2.7		
Posterior wall thickness (mm)			12.6±1.7		
LVEDD (mm)			47±11.5		
LVESD (mm)			32.8±6.5		
Systolic pulmonary artery pressure (mmHg)			43.8±10.3		
Mean aortic gradient (mmHg)			42.8±15.8		
Moderate to severe mitral regurgitation (%)	45	42.8			
Moderate to severe tricuspid regurgitation (%)	35	33.3			
Moderate aortic regurgitation (%)	15	14.3			
Computed tomography measurements					
LVOT diameter (mm)			24.6±2.2		
Aortic annulus diameter (mm)			24.2±1.4		
Left coronary sinus Valsalva diameter (mm)			31.4±2.4		
Right coronary sinus Valsalva diameter (mm)			28.5±2.3		
Non-coronary sinus Valsalva diameter (mm)			31.0±3.0		
Sinus Valsalva height (mm)			23.0±1.8		
LMCA height (mm)			14.4±3.0		
Right coronary artery height (mm)			18.2±3.2		
Moderate leaflet calcification (%)	35	33.3			
Aortic angle (°)			46.8±10.6		
Procedure-related measurements					
Valve size (%)					
26 mm	20	19.0			
29 mm	65	62.0			
34 mm	20	19.0			
Pre-dilatation (%)					
18 mm	5	4.8			
20 mm	30	28.6			
22 mm	5	4.8			
23 mm	10	9.5			
Post-dilatation (%)					
23 mm	20	19.0			
25 mm	30	28.6			
26 mm	5	4.8			
Permanent pacemaker (%)	10	9.5			
Postoperative moderate to severe aortic regurgitation	10	9.5			

SD: Standard deviation; IQR: Interquartile range; CAD: Coronary artery disease; EuroSCORE: European System for Cardiac Operative Risk Evaluation; LVEDD: Left ventricular end-diastolic diameter; LVESD: Left ventricular end-systolic diameter; LVOT: Left ventricular outflow diametern; LMCA: Left main coronary artery.

artery pressure was 43.8±10.3 mmHg, and the mean aortic gradient was 42.8±10.3 mmHg. Notably, 15 (14.3%) patients exhibited moderate to severe AR. The most common valve disease that was more than mild was mitral regurgitation (42.8%; Table 1).

In the preprocedural computed tomography evaluations, the mean left ventricular outflow tract diameter was 24.6±2.2, the mean aortic annulus diameter was 24.2±1.4, the mean left main coronary height was 14.4±3.0, and the mean right coronary height was 18.2±3.2. The sinus of Valsalva diameter, encompassing all three sinuses, yielded a mean measurement of 30.3±2.0. Notably, one-third of the patients exhibited moderate leaflet calcification. The degree of leaflet calcification was assessed using computed tomography, with mild calcification defined as scattered, thin calcifications covering less than 10% of the leaflet area, moderate calcification characterized by thicker calcifications covering 10 to 30% of the leaflet area, and severe calcification involving extensive, dense calcifications covering more than 30% of the leaflet area. Furthermore, the mean aortic angle was 46.8±10.6° (Table 1).

Evolut R self-expandable supra-annular 26-mm valves were used in 19%, 29-mm valves were used in 62%, and 34-mm valves were used in 19%. Predilatation was applied to 47.6% of the patients, and postdilatation was applied to 52.4%. A permanent pacemaker was needed after the procedure in 10 (9.5%) patients, and moderate AR was observed in 10 (9.5%) patients (Table 1).

The study compared pre-TAVI and predischarge echocardiographic parameters. As anticipated, a significant reduction was evident in the mean and peak aortic gradients before discharge (mean postprocedural gradient: 7.5±4.3 mmHg; peak aortic gradient: 14.9±7.7 mmHg; p<0.001). There was no significant difference between the mean EF (48.1±14.1%), left ventricular end-diastolic diameter (LVEDD; 47±11.5 mm), and left ventricular end-systolic diameter (LVESD; 32.8±6.5 mm) before TAVI and the mean EF (49.8±12.3%), LVEDD (48.6±5.3 mm), and LVESD (31.3±6.1 mm) before discharge. A significant decrease was noted in the systolic pulmonary artery pressure before discharge compared to preoperative levels (preoperative: 43.8±10.3; predischarge: 39.6±8.7; p=0.046). Additionally, the prevalence of moderate or higher AR decreased after valve implantation (preoperative: 14.3%; post-TAVI: 11.4%; p=0.033; Table 2).

Patient characteristics affecting the aortic angle were evaluated with Spearman correlation analysis. A positive correlation was observed between interventricular septum thickness, ascending aorta

Table 2
Comparison of preoperative and postoperative echocardiographic measurements

Echocardiographic measurements	Preoperative Mean±SD	Postoperative Mean±SD	*p*
Left ventricular ejection fraction (%) (Prior to TAVI-Prior to discharge)	48.1±14.1	49.8±12.3	0.052
Mean aortic gradient (mmHg) (Prior to TAVI-Prior to discharge)	42.8±15.8	7.5±4.3	<0.001
Peak aortic gradient (mmHg) (Prior to TAVI-Prior to discharge)	66.8±22.4	14.9±7.7	<0.001
LVEDD (mm) (Prior to TAVI-Prior to discharge)	47.0±11.5	48.6± 5.3	0.161
LVESD (mm) (Prior to TAVI-Prior to discharge)	32.8±6.4	31.3±6.1	0.156
sPAP (mmHg) (Prior to TAVI-Prior to discharge)	43.8±10.3	39.6±8.7	0.046
Moderate to severe AR (%) (Prior to TAVI-After TAVI)	%14.3	%11.4	0.033

SD: Standard deviation; TAVI: Transcatheter aortic valve implantation; LVEDD: Left ventricular end-diastolic diameter; LVESD: Left ventricular end-systolic diameter; sPAP: Systolic pulmonary artery pressure; AR: Aortic regurgitation.

Table 3
Clinical characteristics affecting the aortic angle

	Aortic angle	
	Correlation coefficient	*p*
Age	−0.109	0.266
Sex		
Male	0.155	0.114
Body mass index	0.235	0.135
EuroSCORE II	0.084	0.396
Left ventricular ejection fraction (%)	−0.194	0.047
IVS	0.205	0.036
LVEDD	0.072	0.467
Mean aortic gradient	0.172	0.356
Moderate to severe AR	0.235	0.089
LVOT diameter	−0.301	0.002
Aortic annulus diameter	−0.350	0.001
Ascendant aorta diameter	0.280	0.004
Left coronary sinus Valsalva diameter	−0.188	0.055
Right coronary sinus Valsalva diameter	−0.169	0.084
Non-coronary sinus Valsalva diameter	−0.554	0.001
Sinus Valsalva height	−0.225	0.021
LMCA height	−0.157	0.110
RCA height	−0.410	0.001
Moderate to severe leaflet calcification	0.176	0.073

AR: Aortic regurgitation; IVS: Interventricular septum thickness; LVEDD: Left ventricular end-diastolic diameter; AR: Aortic regurgitation; LVOT: Left ventricular outflow diameter; LMCA: Left main coronary artery; RCA: Right coronary artery.

diameter, and aortic angle (p=0.036 and p=0.004, respectively). A negative correlation was observed between EF, left ventricular outflow tract diameter, aortic annulus diameter, noncoronary cuspid sinus Valsalva diameter, sinus Valsalva height, right coronary artery height, and aortic angle (p=0.047, p=0.002, p=0.001, p=0.001, p=0.021, and p=0.001, respectively; Table 3).

A ROC analysis was performed to determine the cutoff value for the aortic angle affecting the AR after TAVI (before postdilatation). An aortic angle of 49.5° was determined as the cutoff value for the development of AR after TAVI, with 56% sensitivity and 50% specificity (area under the curve: 0.653; Figure 1).

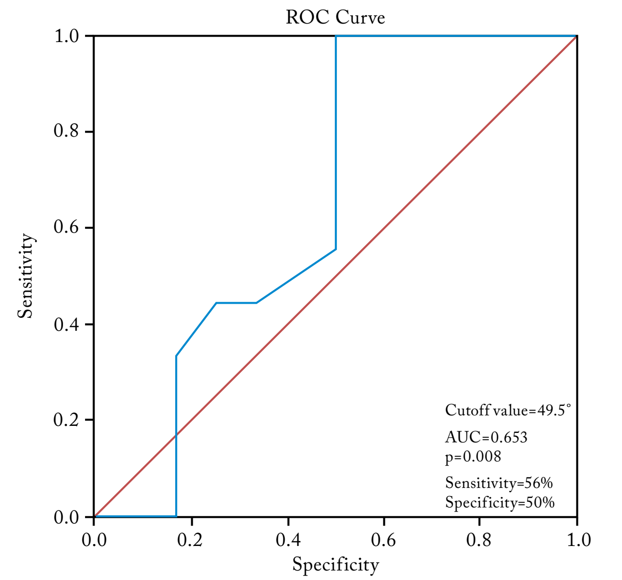
Moderate AR was observed in 12 patients after TAVI (before postdilatation). Of the patients who developed moderate AR before postdilatation, the aortic angle was above 49.5° in 10 (Figure 2).

The change in AR after TAVI (before discharge) compared to before TAVI was examined in all patients. At least one-degree decrease in AR was observed in 40 (38.1%) patients, the same level was observed in 50 (47.6%) patients, and an increase in AR was observed in 15 (14.3%) patients (Figure 3).

When post-TAVI (before postdilatation) AR was divided into none, mild, and moderate, a weak linear relationship was detected between AR and the aortic angle (R^2=0.011; Figure 4).

DISCUSSION

The management of severe AS has evolved significantly, with TAVI emerging as a less invasive



Area AUC				
Test results variable(s): Aortic angle				
Area	SE[a]	Asymptotic sig.[b]	Asymptotic 95% CI	
0.653	0.055	0.008	Lover bound	Upper bound

The test result variable(s): Aortic angle has at least one tie between the positive actual state group and the negative actual state group. Statistics may be biased. a: Under the nonparametric assumption; b: The effect being studied does not exist (if *p* value >0.05).

Figure 1. ROC analysis of the effect of the aortic angle on AR after TAVI.

AUC: Area under the curve; ROC: Receiver operating characteristic; AR: Aortic regurgitation; TAVI: Transcatheter aortic valve implantation; SE: Standard error; CI: Confidence interval.

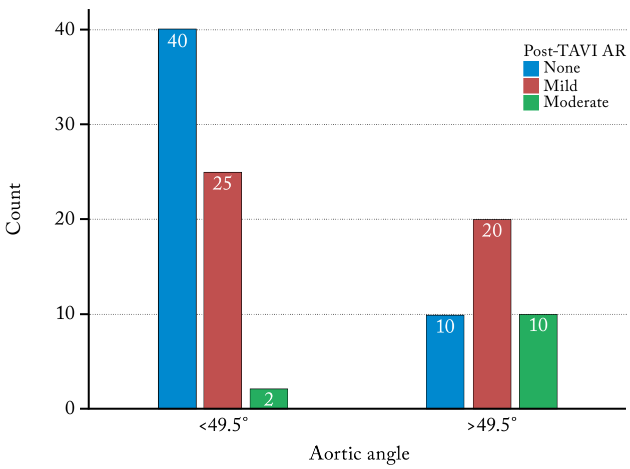


Figure 2. The graphical representation of the AR observed in patients according to the cutoff value of the aortic angle determined according to ROC analysis with a column chart.

AR: Aortic regurgitation; ROC: Receiver operating characteristic.

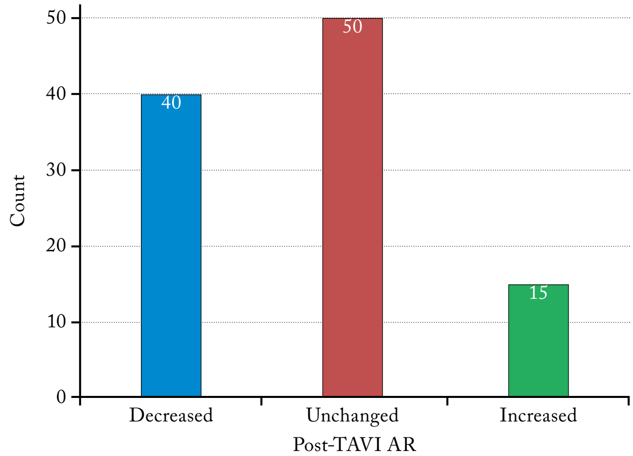


Figure 3. The graphical representation of the change in AR in the echocardiography performed after TAVI (before discharge) compared to before TAVI with a bar graph.

TAVI: Transcatheter aortic valve implantation; AR: Aortic regurgitation.

alternative to surgical aortic valve replacement. However, complications after TAVI, notably AR, remain a concern. This observational study delves into the predictive role of the aortic angle in post-TAVI AR and explores its correlations with various clinical and demographic factors, shedding light on the significance of this anatomical parameter in TAVI outcomes.

In line with our investigation, Roule et al.[19] demonstrated an association between increased angulation between the ascending aorta and the left ventricle long axis and higher rates of AR after TAVI, independent of other potential correlations. Conversely, conflicting findings emerged from other studies. One study suggested that an aortic angle ≥48° did not impact procedural success or in-hospital outcomes and recommended against considering it when determining valve selection.[20] Another study indicated that the aortic angle influenced procedural success in balloon-expandable valves but had no effect on self-expandable valves.[21]

Our study aligns with prior research, confirming the significance of the aortic angle in predicting AR following TAVI. The identified cutoff angle of 49.5° holds merit in assessing risk and forecasting outcomes for TAVI patients. Notably, our study reveals a correlation between higher aortic angles and the development of moderate AR after TAVI, albeit with a weak linear relationship. These insights underscore the importance of thorough preprocedural evaluations,

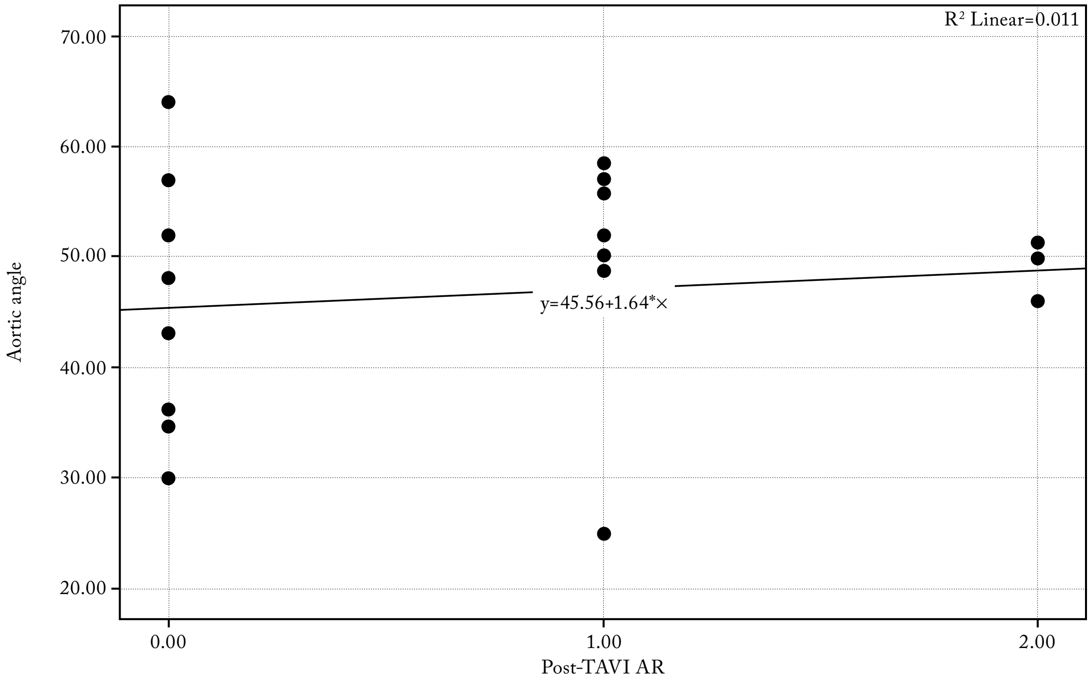


Figure 4. The graphical representation of the linear relationship between aortic insufficiency and the aortic angle after TAVI (before postdilation) with a scatter plot graph.

TAVI: Transcatheter aortic valve implantation; AR: Aortic regurgitation.

emphasizing the necessity of meticulous assessment of aortic anatomy to anticipate and manage post-TAVI complications effectively.

Our investigation into patient characteristics influencing the aortic angle revealed potential predictors for post-TAVI outcomes. Positive correlations with interventricular septum thickness and ascending aorta diameter, alongside negative correlations with parameters such as EF, left ventricular outflow tract diameter, aortic annulus diameter, and sinus of Valsalva dimensions, provide nuanced insights into anatomical factors influencing the aortic angle. These correlations offer the potential for risk stratification and personalized approaches in TAVI procedures.

Although there is a lack of studies investigating specific associations between the aortic angle and interventricular septal hypertrophy, the study by Yoshitani et al.[22] indicated that surgical aortic valve replacement was more effective in improving functional impairment in the presence of interventricular septal hypertrophy in AS patients compared to TAVR. Additionally, sharper angulation of the aortic arch has been linked to late AR after arterial switch surgery for ascending aortic dilatation and transposition of the great arteries.[23] This highlights the diverse impact of aortic geometry on various cardiac conditions.

A decrease in left ventricular EF can remodel the left ventricle, resulting in a leftward shift and a flatter appearance at the apex. This alteration in shape helps elucidate the negative relationship between an increased aortic angle and EF.

Our study's focus on patients without advanced annular calcification, utilizing Evolut R self-expandable supra-annular valves, characterizes a distinct subset of TAVI patients. This focused approach provides unique insights into this subset, potentially facilitating more refined prognostic assessments for this subgroup.

The observed improvements in aortic gradients, pulmonary artery pressures, and the reduction in moderate or higher AR after TAVI underscore the procedure's efficacy in managing valvular pathologies.[24] These improvements highlight the clinical benefits and success of TAVI in relieving symptomatic burden among patients with severe AS.

Our study aimed to identify the primary risk factors contributing to aortic insufficiency following TAVI procedures, with a particular focus on the aortic angle. One of the significant findings was the association between an increased aortic angle and a higher incidence of aortic insufficiency. To ensure a more accurate assessment of this relationship, patients with bicuspid aortic valves were excluded from our study. This exclusion was critical in eliminating a well-known confounding factor that could independently affect the outcomes. We acknowledge that aortic insufficiency is multifactorial, and other potential risk factors such as leaflet calcification extent, annular dimensions, bicuspid aortic valves, and overall valve morphology could play crucial roles. Our findings emphasize the need for future studies to incorporate a broader evaluation of these additional risk factors. A comprehensive analysis that includes various anatomical and procedural factors will provide a more holistic understanding of the determinants of aortic insufficiency after TAVI.

This study had several limitations that warrant consideration. The study's single-center observational design and limited sample size might constrain the generalizability of the findings. Additionally, potential confounders not accounted for in the analysis, incomplete medical records, and retrospective data collection could introduce bias due to missing information. While correlations were established, determining causation necessitates further prospective investigations encompassing comprehensive multifactorial analyses.

In conclusion, this study highlights the pivotal role of the aortic angle in predicting AR after TAVI, establishing a crucial threshold at 49.5°. Investigating correlations between the aortic angle and patient characteristics revealed potential predictors for post-TAVI outcomes, offering avenues for further exploration. The observed improvements in aortic gradients, pulmonary artery pressures, and decreased prevalence of moderate or higher AR after TAVI underscore the procedure's efficacy in managing valvular pathologies. While a weak linear correlation between AR and the aortic angle was noted, the study emphasizes the significance of meticulous preprocedural assessments for predicting and managing complications.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Conceived of the presented idea: T.O., F.P. Developed the theory and performed the computations: F.P.; Verified the analytical methods: B.Y.; Supervised the findings of this work: T.O., B.Y. All authors discussed the results and contributed to the final manuscript.

Conflict of Interest: The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

Funding: The authors received no financial support for the research and/or authorship of this article.

REFERENCES

1. Généreux P, Stone GW, O'Gara PT, Marquis-Gravel G, Redfors B, Giustino G, et al. Natural history, diagnostic approaches, and therapeutic strategies for patients with asymptomatic severe aortic stenosis. J Am Coll Cardiol 2016;67:2263-88. doi: 10.1016/j.jacc.2016.02.057.
2. Gottlieb M, Long B, Koyfman A. Evaluation and management of aortic stenosis for the emergency clinician: An evidence-based review of the literature. J Emerg Med 2018;55:34-41. doi: 10.1016/j.jemermed.2018.01.026.
3. Bhatia N, Basra SS, Skolnick AH, Wenger NK. Aortic valve disease in the older adult. J Geriatr Cardiol 2016;13:941-4. doi: 10.11909/j.issn.1671-5411.2016.12.004.
4. Rana M. Aortic valve stenosis: Diagnostic approaches and recommendations of the 2021 ESC/EACTS guidelines for the management of valvular heart disease -a review of the literature. Cardiol Cardiovasc Med 2022;6:315-24. doi: 10.26502/fccm.92920267.
5. Osnabrugge RL, Mylotte D, Head SJ, Van Mieghem NM, Nkomo VT, LeReun CM, et al. Aortic stenosis in the elderly: Disease prevalence and number of candidates for transcatheter aortic valve replacement: A meta-analysis and modeling study. J Am Coll Cardiol 2013;62:1002-12. doi: 10.1016/j.jacc.2013.05.015.
6. Carità P, Coppola G, Novo G, Caccamo G, Guglielmo M, Balasus F, et al. Aortic stenosis: Insights on pathogenesis and clinical implications. J Geriatr Cardiol 2016;13:489-98. doi: 10.11909/j.issn.1671-5411.2016.06.001.
7. Kanwar A, Thaden JJ, Nkomo VT. Management of patients with aortic valve stenosis. Mayo Clin Proc 2018;93:488-508. doi: 10.1016/j.mayocp.2018.01.020.
8. Kalogeropoulos AS, Redwood SR, Allen CJ, Hurrell H, Chehab O, Rajani R, et al. A 20-year journey in transcatheter aortic valve implantation: Evolution to current eminence. Front Cardiovasc Med 2022;9:971762. doi: 10.3389/fcvm.2022.971762.
9. Panayiotides IM, Nikolaides E. Transcatheter Aortic Valve Implantation (TAVI): Is it time for this intervention to be applied in a lower risk population? Clin Med Insights Cardiol 2014;8:93-102. doi: 10.4137/CMC.S19217.
10. Voigtländer L, Seiffert M. Expanding TAVI to low and intermediate risk patients. Front Cardiovasc Med 2018;5:92. doi: 10.3389/fcvm.2018.00092.

11. van Ginkel DJ, Brouwer J, van Hemert ND, Kraaijeveld AO, Rensing BJWM, Swaans MJ, et al. Major threats to early safety after transcatheter aortic valve implantation in a contemporary cohort of real-world patients. Neth Heart J 2021;29:632-42. doi: 10.1007/s12471-021-01638-8.
12. Laborde JC, Brecker SJ, Roy D, Jahangiri M. Complications at the time of transcatheter aortic valve implantation. Methodist Debakey Cardiovasc J 2012;8:38-41. doi: 10.14797/mdcj-8-2-38.
13. Stähli BE, Maier W, Corti R, Lüscher TF, Jenni R, Tanner FC. Aortic regurgitation after transcatheter aortic valve implantation: Mechanisms and implications. Cardiovasc Diagn Ther 2013;3:15-22. doi: 10.3978/j.issn.2223-3652.2013.02.01.
14. Collas VM, Paelinck BP, Rodrigus IE, Vrints CJ, Bosmans JM. Aortic regurgitation after Transcatheter Aortic Valve Implantation (TAVI) - Angiographic, echocardiographic and hemodynamic assessment in relation to one year outcome. Int J Cardiol 2015;194:13-20. doi: 10.1016/j.ijcard.2015.05.015.
15. Dujardin KS, Enriquez-Sarano M, Schaff HV, Bailey KR, Seward JB, Tajik AJ. Mortality and morbidity of aortic regurgitation in clinical practice. A long-term follow-up study. Circulation 1999;99:1851-7. doi: 10.1161/01.cir.99.14.1851.
16. Schoenhagen P, Hausleiter J, Achenbach S, Desai MY, Tuzcu EM. Computed tomography in the evaluation for Transcatheter Aortic Valve Implantation (TAVI). Cardiovasc Diagn Ther 2011;1:44-56. doi: 10.3978/j.issn.2223-3652.2011.08.01.
17. Randhawa A, Gupta T, Singh P, Aggarwal A, Sahni D. Description of the aortic root anatomy in relation to transcatheter aortic valve implantation. Cardiovasc Pathol 2019;40:19-23. doi: 10.1016/j.carpath.2019.01.005.
18. Gorla R, De Marco F, Garatti A, Bianchi G, Popolo Rubbio A, Acerbi E, et al. Impact of aortic angle on transcatheter aortic valve implantation outcome with Evolut-R, Portico, and Acurate-NEO. Catheter Cardiovasc Interv 2021;97:E135-45. doi: 10.1002/ccd.28957.
19. Roule V, Placente A, Sabatier R, Bignon M, Saplacan V, Ivascau C, et al. Angles between the aortic root and the left ventricle assessed by MDCT are associated with the risk of aortic regurgitation after transcatheter aortic valve replacement. Heart Vessels 2018;33:58-65. doi: 10.1007/s00380-017-1032-1.
20. Medranda GA, Musallam A, Zhang C, Rappaport H, Gallino PE, Case BC, et al. The impact of aortic angulation on contemporary transcatheter aortic valve replacement outcomes. JACC Cardiovasc Interv 2021;14:1209-15. doi: 10.1016/j.jcin.2021.03.027.
21. Abramowitz Y, Maeno Y, Chakravarty T, Kazuno Y, Takahashi N, Kawamori H, et al. Aortic angulation attenuates procedural success following self-expandable but not balloon-expandable TAVR. JACC Cardiovasc Imaging 2016;9:964-72. doi: 10.1016/j.jcmg.2016.02.030.
22. Yoshitani H, Isotani A, Song JK, Shirai S, Umeda H, Jang JY, et al. Surgical as opposed to transcatheter aortic valve replacement improves basal interventricular septal hypertrophy. Circ J 2018;82:2887-95. doi: 10.1253/circj.CJ-18-0390.
23. Agnoletti G, Ou P, Celermajer DS, Boudjemline Y, Marini D, Bonnet D, et al. Acute angulation of the aortic arch predisposes a patient to ascending aortic dilatation and aortic regurgitation late after the arterial switch operation for transposition of the great arteries. J Thorac Cardiovasc Surg 2008;135:568-72. doi: 10.1016/j.jtcvs.2007.10.020.
24. Radhoe SP, Veenis JF, Van Mieghem NM, Brugts JJ. The effect of transcatheter aortic valve implantation on pulmonary artery pressures in a patient suffering from chronic heart failure: A case report. Eur Heart J Case Rep 2021;5:ytab112. doi: 10.1093/ehjcr/ytab112.