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# Increased Aortic Angulation in Transcatheter Aortic Valve Implantation—Still a Challenging Anatomy?

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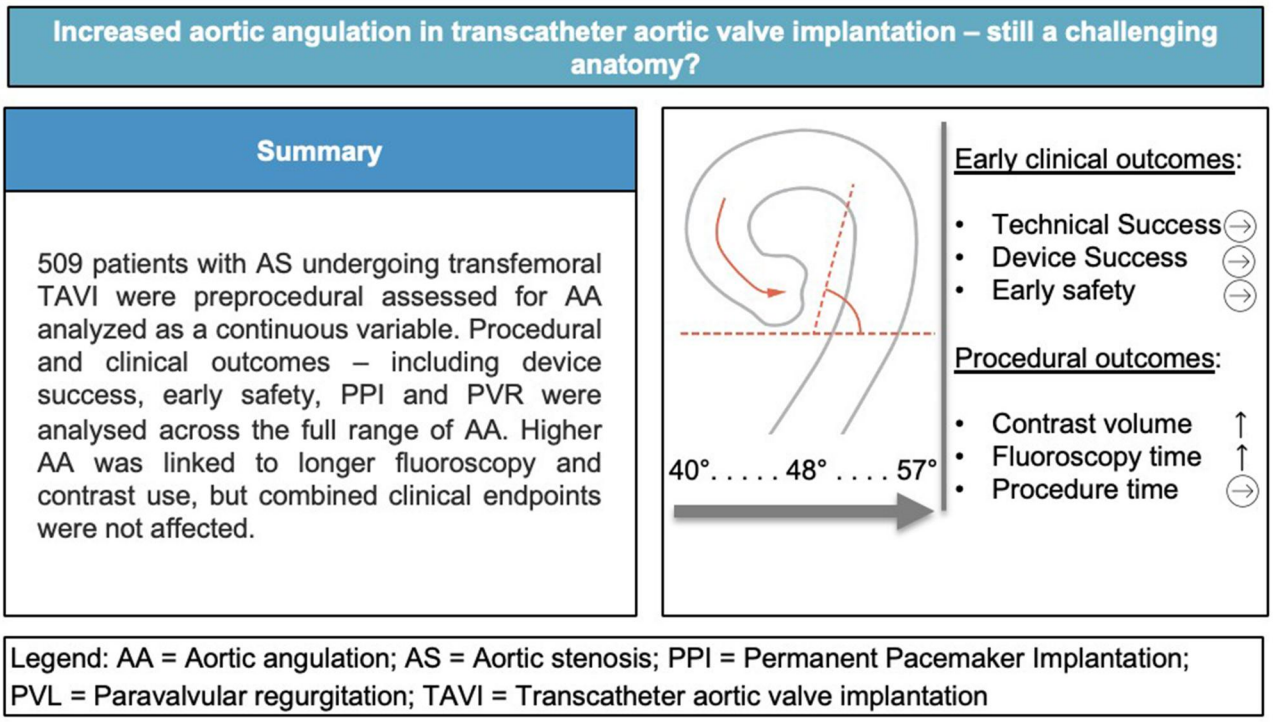
## Graphical abstract

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## Abstract

**Objectives:** Increased aortic angulation (AA) is anatomically challenging during transcatheter aortic valve implantation (TAVI) and may affect procedural outcomes. This study evaluates the clinical and procedural impact of AA in contemporary TAVI procedures.

**Methods:** This retrospective single-centre observational study included 509 consecutive patients undergoing transfemoral TAVI between January 2021 and December 2024. The primary end-point was device success according to VARC-3 criteria. Secondary endpoints included technical success, early safety at 30 days, procedural time, fluoroscopy time, contrast volume, paravalvular regurgitation (PVR), and permanent pacemaker implantation (PPI). Multivariable logistic and linear regression models were used to assess the association between AA (in degrees) and clinical outcomes. Receiver operating characteristic (ROC) and spline regression analyses were used to evaluate potential threshold effects.

**Results:** Device success at discharge was achieved in 89.4% (455/509) of patients, technical success in 96.3% (490/509), and early safety at 30 days in 75.6% (385/509). Aortic angulation did not significantly influence device success (adjusted odds ratio [aOR]: 0.974, 95% CI: 0.938-1.012, $P = .175$), technical success (aOR 1.034; 95% CI 0.980-1.091; $P = .22$), or early safety (aOR: 0.994, 95% CI: 0.968-1.020, $P = .633$). Similarly, no association was observed between AA and PPI (aOR 1.016; 95% CI 0.984-1.050; $P = .34$) and PVR. However, AA significantly correlated with increased fluoroscopy times (coefficient: 0.073, SE: 0.026; $P = .006$) and greater contrast usage (coefficient: 0.406, SE: 0.194; $P = .037$).

**Conclusions:** While higher AA increased procedural imaging demand, it did not adversely affect device performance or clinical safety outcomes after TAVI. Importantly, outcomes remained consistent across prosthesis types.


**Keywords:** heart valve; aortic valve; aortic valve stenosis; transcatheter aortic valve implantation.

## INTRODUCTION

Transcatheter aortic valve implantation (TAVI) has emerged as an alternative therapy for patients with severe symptomatic aortic valve stenosis, particularly in elderly populations and those with increased surgical risk. With growing experience and continuous refinement of prosthesis technology, attention has increasingly shifted towards understanding the influence of individual anatomical characteristics on procedural feasibility and clinical outcomes.[1] Among these, aortic angulation (AA) has gained recognition as a potentially relevant procedural variable.[2,3] In the literature, AA is often simplified into a binary variable, as many authors proposed the concept of a horizontal aorta (HA), likely to facilitate clinical decision-making. Typically defined by an angulation $\geq 48^{\circ}$ between the aortic annulus and the horizontal plane in coronal projection on computed tomography, HA is supposed to hinder optimal coaxial alignment of the delivery system and complicate accurate valve deployment.[4]

Contemporary results from the HORSE registry and multiple case reports suggest that the impact of AA on outcomes may vary depending on valve design.[5,6] However, the evidence remains inconclusive, with inconsistent use of later generation transcatheter valve types. Moreover, the proposed dichotomization of AA into a binary HA variable remains questionable, as the suggested cut-off point lacks strong statistical support and clinical justification. Given these controversies, along with recent advances in TAVI prostheses, the relevance of increased AA warrants reassessment.[7] Instead of relying on a simplified binary classification, this study investigates AA as a continuous anatomical variable, aiming to better reflect the physiological spectrum and procedural realities encountered during TAVI.

This approach enables a more refined understanding of how varying degrees of AA may influence procedural success and short-term clinical outcomes in patients undergoing transfemoral TAVI with contemporary transcatheter heart valves (THV).

## MATERIALS AND METHODS

### Study design and patient population

This retrospective, single-centre observational study included 607 consecutive patients with severe aortic stenosis who underwent transfemoral TAVI at the University Hospital Augsburg between January 2021 and December 2024. Patients were excluded if they exhibited bicuspid or unicuspid aortic valve morphology, underwent valve-in-valve procedures, received TAVI via alternative access routes, or presented with isolated aortic regurgitation.

### AA assessment and group stratification

Preprocedural contrast-enhanced multidetector computed tomography (MDCT) was performed in all patients to assess aortic root and vascular anatomy. The AA was measured using dedicated post-processing software (3mensio Structural Heart™, Pie Medical Imaging, The Netherlands), defined as the angle between the horizontal plane and the centerline of the ascending aorta in the coronal orientation in 3-cusp view (**Figure 1**).

### Endpoints

The primary combined end-point was device success at hospital discharge, defined according to the Valve Academic Research Consortium-3 (VARC-3) criteria.[8] Secondary endpoints comprised technical success at the end of the procedure (according to the VARC-3 criteria), early safety at 30 days postintervention (according to the VARC-3 criteria), procedure time, fluoroscopy time, contrast medium usage, paravalvular regurgitation (PVR) and new permanent pacemaker implantation (PPI).

### Statistical analysis

Categorical data are presented as counts (*n*) and percentages (%), and continuous variables as means ± SD. Group

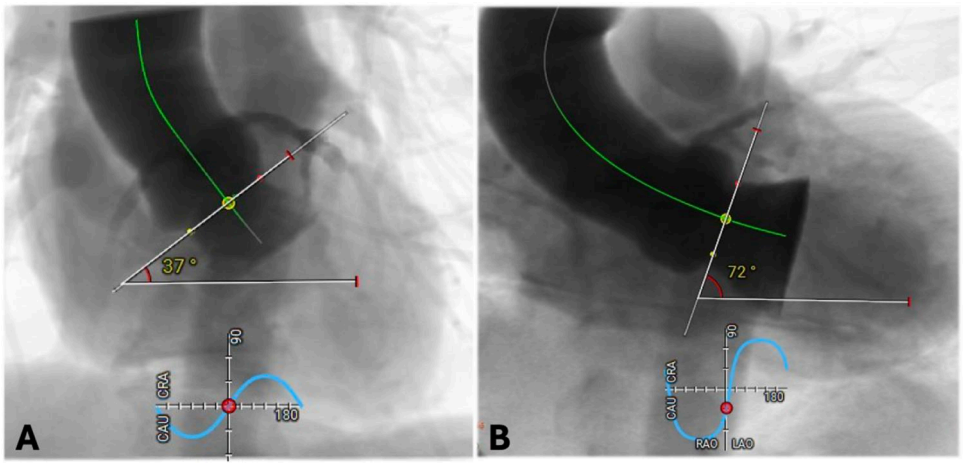


**Figure 1.** Representative Fluoroscopic Images. (A) Decreased aortic angulation, (B) increased aortic angulation between the annular plane and the horizontal reference line during TAVI planning

comparisons for categorical variables were performed using the $\chi^2$ test and Fisher's exact test. For continuous data, an independent 2-tailed Student *t*-test or Mann-Whitney *U*-test was used if data were normally or non-normally distributed, respectively.

Univariable and multivariable binary logistic regression models for dichotomous outcomes of interest (device success, early safety, technical success, new PPI and PVR) and univariable linear regression models (procedure duration, contrast agent volume, fluoroscopy time) were built to explore the effect of AA, analysed as a continuous variable, on the outcomes of interest. The linearity assumption for the continuous predictor AA was evaluated using restricted cubic spline functions to assess potential non-linear relationships. Covariates were selected based on clinical relevance and exiting literature, complemented by variables showing a *P*-value <.10 in univariable screening. The models were adjusted for relevant clinical covariates including independent predictors including age, sex, peripheral vascular disease, and postdilatation. For the analysis of new PPI, models were further adjusted for the presence of pre-existing left or right bundle branch block. Variables with substantial missingness or no univariable association were excluded to maintain model stability and minimize data loss. To assess model-assumption violations in linear regression models, we performed Shapiro-Wilk, Breusch-Pagan and Durbin-Watsons test and calculated variance inflation factors. Interaction effects between AA and valve type were tested to explore effect modification.

As dichotomization of the AA value has been proposed in the past and might have a relevant effect on clinical decision-making, a post hoc ROC analysis and spline regression analysis were performed to explore the optimal AA cut-off value for predicting device success at hospital discharge. Additional exploratory subanalyses, utilizing established definitions from the available literature, defining HA as an angulation ≥48°, were performed.[4]

Missing data were minimal and considered missing completely at random, therefore no imputation was performed, and a complete case analysis was performed. Statistical significance was defined by a 2-sided *P*-value <.05. All reported *P*-values are nominal. Statistical analyses were performed using the statistical software R (version 4.4.2; R Core Team 2021).

**Table 1.** Baseline Characteristics

| Variables | All patients N = 509 N (%) |
|---|---|
| Age (years), mean ± SD | 80.4 ± 6.8 |
| Gender female | 222 (43.6) |
| Body mass index (kg/m$^2$), mean ± SD | 27.7 ± 5.6 |
| EuroScore II (%), mean ± SD | 4.2 ± 4 |
| Hypertension | 452 (88.8) |
| Diabetes mellitus | 169 (33.2) |
| Dyslipidaemia | 400 (78.6) |
| Prior stroke | 64 (12.6) |
| Chronic obstructive pulmonary disease | 64 (12.6) |
| Immobility | 75 (14.7) |
| Prior myocardial infarction | 118 (23.2) |
| Chronic kidney disease | 131 (25.7) |
| Dialysis | 13 (2.6) |
| New York Heart Association III | 276 (54.2) |
| New York Heart Association IV | 30 (5.9) |
| Atrial fibrillation | 142 (27.9) |
| Prior permanent pacemaker | 26 (5.1) |
| Intraventricular conduction disturbances | 135 (26.5) |
| Aortic angulation (°), mean ± SD | 48.1 ± 8.2 |

## RESULTS

Out of 607 patients screened, 509 were included in the final analysis following exclusion of those with bicuspid or unicuspid aortic valve morphology ($N = 30$), valve-in-valve procedures ($N = 34$), non-transfemoral access routes ($N = 29$), and isolated aortic regurgitation ($N = 5$). Baseline demographic and clinical variables are summarized in **Table 1**. Discharge parameters are detailed in **Table 2**.

### Endpoints analyses

Device success at discharge was achieved in 89.4% of patients (455/509), with no effect of AA seen (adjusted odds ratio [OR]:

**Table 2.** Discharge Characteristics

| Variables | All patients N = 509 N (%) |
|---|---|
| Length of stay (days), mean ± SD | 6.4 ± 8.5 |
| Intraoperative mortality | 2 (0.4) |
| 30 days mortality | 7 (1.4) |
| Permanent pacemaker implantation | 68 (13.4) |
| New Left bundle branch block | 106 (20.9) |
| New Atrioventricular-block III | 59 (11.7) |
| New stroke | |
| Without symptoms | 7 (1.4) |
| With symptoms | 9 (1.8) |
| Delirium | 30 (5.9) |
| New myocardial infarction | 1 (0.2) |
| Left ventricular ejection fraction (%), mean ± SD | 52.3 ± 8.9 |
| Paravalvular regurgitation | |
| Mild | 80 (15.9) |
| Moderate | 5 (1) |
| Severe | 1 (0.2) |
| Maximum pressure gradient (mm Hg), mean ± SD | 16.7 ± 8.9 |
| Mean pressure gradient (mm Hg), mean ± SD | 8.7 ± 4.8 |

0.974, 95% CI: 0.938-1.012, $P = .175$). Technical success at the end of the procedure was recorded in 96.3% of cases (490/509). Similarly, early safety at 30 days was observed in 75.6% (385/509) of patients with no effect of AA on the outcome (adjusted OR: 0.994, 95% CI: 0.968-1.020, $P = .633$). An overview of all composite endpoints according to VARC-3 criteria across groups is provided in **Figure 2** and **Table S7**. Results of the uni- and multivariable regression analyses are summarized in **Table 3**.

In linear regression analyses, AA was independently associated with increased fluoroscopy time ($\beta = 0.073$, SE = 0.026, $P = .006$) and higher use of contrast agent volume ($\beta = 0.406$, SE = 0.194, $P = .037$; **Figure 3A and B**). The overall mean fluoroscopy time was 8.9 ± 4.9 min, and the mean contrast agent volume was 72.1 ± 36.1 mL. To contextualize these findings, we stratified the cohort into 4 predefined AA groups, revealing a stepwise increase in both parameters with rising angulation (**Figure S1**). The incidence of new PPI within 30 days was 14.1% (68/483), with no statistically significant association with AA (adjusted OR: 1.016, 95% CI: 0.984-1.050, $P = .34$). Similarly, PVR showed no association with AA (adjusted OR: 1.013, 95% CI: 0.982-1.044, $P = .412$).

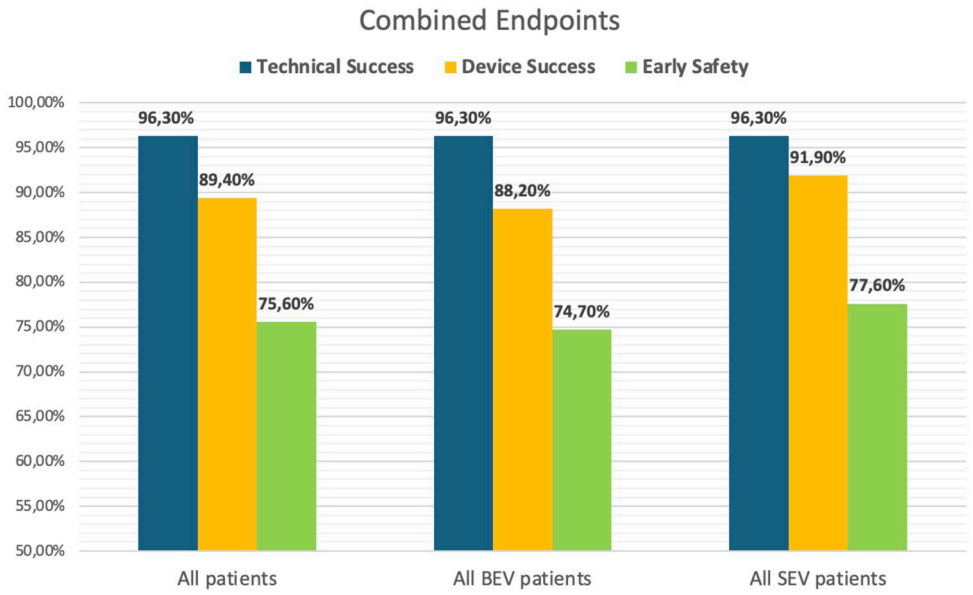


**Figure 2.** Combined Endpoints in Overall Cohort

**Table 3.** Uni- and Multivariable Logistic Regression Models Evaluating the Association between Aortic Angulation and Composite Endpoints

| | Univariable | | | Multivariable | | |
|---|---|---|---|---|---|---|
| | OR | 95% CI | *P*-value | OR | 95% CI | *P*-value |
| Device success | 0.976 | 0.940-1.014 | .201 | 0.974 | 0.938-1.012 | .175 |
| Early safety | 0.991 | 0.966-1.018 | .519 | 0.994 | 0.968-1.020 | .633 |
| PVR | 1.010 | 0.981-1.041 | .491 | 1.013 | 0.982-1.044 | .412 |
| PPI | 1.015 | 0.984-1.048 | .34 | 1.016 | 0.984-1.050 | .34 |

Abbreviations: CI, confidence interval; OR, odds ratio; PPI, Permanent pacemaker implantation; PVR, paravalvular regurgitation.

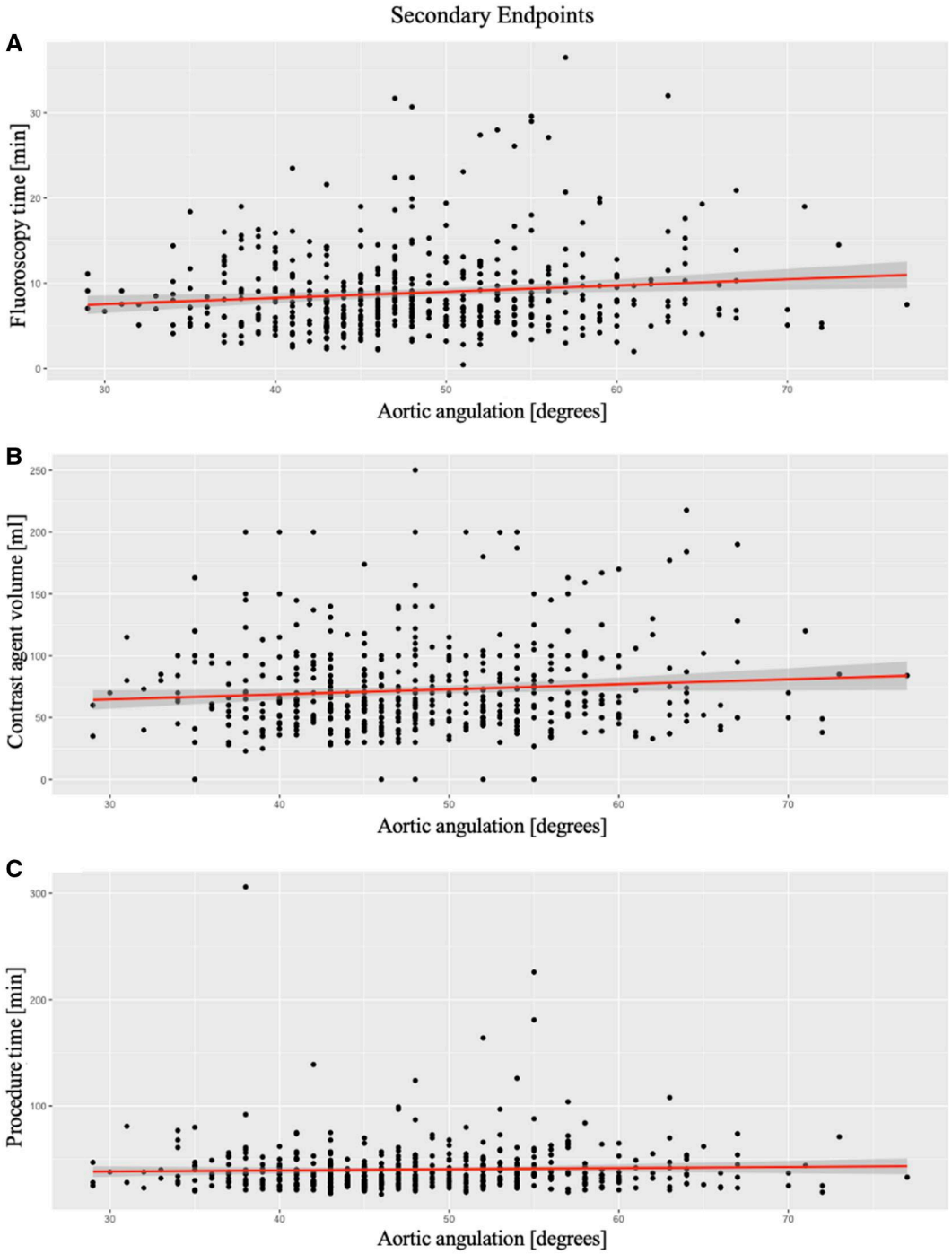


**Figure 3.** Association Between Aortic Angulation and Secondary Procedural Parameters. (A) Fluoroscopy time, (B) contrast agent volume, and (C) procedure duration are plotted against aortic angulation.

## Cut-off point analysis

In a post hoc receiver operator curve-based cut-off analysis, AA did not demonstrate sufficient discriminatory ability for predicting device success or early safety. The area under the ROC curve was 0.571, and no optimal threshold could be determined, supporting the treatment of AA as a continuous rather than dichotomous variable and highlighting the limited clinical utility of this approach (**Figure S2**). Spline regression likewise showed no meaningful inflection points (**Figure S3**), suggesting a continuous, non-threshold-dependent relationship. This was supported by a spline-based logistic regression model adjusted for age and sex (**Figure S4**).

## Subgroup analysis by valve type

In the overall cohort, subgroup analysis by THV type, with the population split in ballon-expandable valves (BEVs) and self-expanding valve (SEV) cohorts revealed no significant differences

in primary outcomes. Device success at discharge was achieved in 88.2% of patients treated with BEV, compared to 91.9% in those treated with SEV ($P = .268$). Only contemporary-generation THVs were implanted. **Figure S5** illustrates the distribution of implanted valve brands. Similarly, early safety at 30 days was documented in 74.7% of BEV recipients versus 77.6% of SEV recipients ($P = .546$). Supplementary uni- and multivariable regression analyses stratified by valve type are presented in **Tables S1–S6**. No significant effect of AA on the endpoints of interest was seen on subgroup analyses.

## DISCUSSION

In this retrospective single-centre study, we systematically investigated the impact of AA on technical feasibility, procedural complexity, and short-term clinical outcomes following transfemoral TAVI. Although higher AA was associated with increased procedural resource utilization, it did not adversely affect device success, early safety, PVR or PPI rates. Receiver-operating curve and spline regression analyses failed to identify a meaningful threshold, supporting a non-dichotomous interpretation of this anatomical factor. These findings align with and reinforce previous investigations, offering reassurance regarding the procedural safety of TAVI in patients with challenging aortic anatomy.

### Comparison of clinical outcomes

In line with our findings, Medranda et al. reported no significant differences in device success, 30-day outcomes, or PPI rates between HA and non-HA patients when using contemporary BEV and SEV.[9] Similarly, Di Stefano et al. found no adverse effect of HA on device success or short-term complications using second-generation devices, despite reporting longer fluoroscopy and radiation exposure in HA patients.[10] These observations were recently supported by Eckel et al., who reported similar rates of technical success (93.1%) and device success (up to 88.6%) as in our cohort.[11] We confirmed these trends using multivariable analyses, demonstrating that AA as a continuous variable was not associated with device failure, nor with increased risk of early adverse events.

In contrast, Veulemans et al. observed significantly higher 30-day mortality (3.3% vs 0.4%), stroke (7.1% vs 2.7%), and major vascular complications in HA patients treated exclusively with self-expanding CoreValve Evolut R/PRO (Medtronic) devices. The differing outcomes may be attributable to higher repositioning rates, asymmetric calcifications and potentially centre-specific factors.[3] Moreover, since our analyses do not support the dichotomization of AA into a binary variable, the observed differences may reflect issues related to the use of inappropriate cut-off points rather than a relevant effect of HA on clinical outcomes. In our study, AA did not emerge as an independent predictor of adverse outcomes, suggesting that angulation alone is not inherently associated with inferior clinical results across valve types.

A recently published meta-analysis by Khalefa et al. suggested an association between HA and adverse outcomes post-TAVI, diverging from our findings. However, the analysis pooled heterogeneous data from earlier TAVI eras, lacked consistent angulation definitions, and did not account for key confounders. These differences may explain the discrepancy and limit direct comparability.[12]

### Procedural complexity and imaging correlates

Consistent with Popma et al., who reported slightly prolonged procedure times in patients with higher AA without differences in major outcomes, we observed significantly longer fluoroscopy times and increased contrast agent use with increasing AA, supporting the notion of increased procedural imaging burden and resource utilization.[13] However, procedure duration itself did not differ significantly, suggesting that complexity is importantly related to other factors than only device positioning. These findings also highlight the nuanced relationship between aortic root geometry and periprocedural outcomes, which was first systematically explored by Sherif et al.[14] In their early single-centre study, they demonstrated that the occurrence of PVR after TAVI was not solely dependent on prosthesis type and identified a high AA as an independent predictor of PVR. However, in the contemporary setting, MDCT offers a more reliable and reproducible modality to evaluate aortic geometry and plan device selection and positioning accordingly.[15] In parallel, newer-generation SEVs have addressed this anatomical challenge through technical refinements, all contributing to a marked reduction in significant PVR.[16] Moreover, BEVs have consistently demonstrated favourable outcomes in patients with AA due to their flexible catheter design, which enables improved coaxiality.[17]

Gorla et al. and Kaneko et al. emphasized that not only angulation but also curvature of the aortic trajectory affects valve delivery and final implantation depth—especially in self-expanding platforms.[6,7] Our data add to this understanding by showing that even in routine practice, increasing AA affects fluoroscopic and contrast burden, reinforcing the need for precise imaging and planning. Further perspective is provided by a sub-analysis of the HORSE registry, which examined AA in over 4000 transfemoral TAVI patients. While the authors identified a mean angulation of approximately 49.4° as a potential threshold for defining HA, their study emphasized the anatomical variability of this parameter and its uncertain predictive value.[18] In contrast to their suggestion that AA might serve as a stratification tool, our findings indicate that horizontal AA—when managed with modern THVs and image-guided planning—does not independently determine success or early safety. These contrasting observations underline the evolving nature of TAVI practice, where anatomical challenges such as HA may be increasingly neutralized by device improvements and procedural standardization.

### Device type and interaction effects

Our subgroup and interaction analyses did not reveal any significant effect modification between AA and prosthesis type. While early concerns regarding SEV in HA anatomy were prominent—due to their delivery stiffness and limited repositionability—this appears less relevant in the current generation of devices. Notably, the HORSE registry reported increased device failure in HA patients treated with Evolut R/PRO, but not with ACURATE neo valves.[5] In contrast, our balanced cohort showed similar short-term performance across device types, suggesting that operator experience and procedural strategy may offset anatomic challenges. The ITAL-neo registry provides pivotal evidence on the performance of the self-expanding ACURATE Neo2 THV in

patients with HA. In this multicentre cohort analysis, among 900 patients undergoing TAVI, 407 exhibited HA. The study found that while HA was an independent risk factor for developing moderate or greater PVR regardless of the THV implanted, the use of the ACURATE Neo2 was associated with a significantly lower rate of ≥ moderate PVR compared to its predecessor, the ACURATE neo (5% vs 15%; $P < .001$). Notably, in the Neo2 group, there was no correlation between the degree of AA and the incidence of PVR, suggesting that the design enhancements in the Neo2 may mitigate the adverse effects of HA on valve sealing.[19]

These findings align with our study's observations, where modern THV systems demonstrated resilience against the challenges posed by HA, maintaining high procedural success rates and favourable early clinical outcomes. The ITAL-neo registry's results underscore the importance of device selection in managing complex aortic anatomies and support the notion that advancements in THV design can overcome anatomical hurdles such as HA. A brief procedural note by Kim et al. on the ACURATE neo system highlights that HA may increase technical difficulty due to the stiffness of the delivery catheter and the need for precise coaxiality. Nonetheless, with appropriate preprocedural planning and operator experience, successful implantation remains feasible even in challenging anatomies.[20]

While our study focused on standard transfemoral approaches, case reports such as Marchese et al. demonstrated the feasibility of snare-assisted navigation in extreme HA combined with other complex aortic pathologies.[21] Although such techniques were not required in our cohort, they highlight the procedural adaptability necessary for managing extreme anatomy. These observations are in line with the commentary by Abdel-Wahab et al., who acknowledged that despite technological progress, HA remains a relevant procedural challenge—particularly with long-frame, non-steerable SEVs.[22] They emphasized that while newer-generation devices and improved operator technique have reduced the clinical impact of HA, extreme angulations may still pose risks such as impaired coaxial alignment and malposition. In contrast, our findings suggest that when using modern THVs with meticulous preprocedural planning, AA does not significantly compromise procedural success or early clinical outcomes—even without the need for alternative access or advanced manoeuvres.

### Definition and conceptual relevance of HA

The commonly used definition of HA—typically an angulation ≥ 48° in the coronal plane—is based on retrospective observations and lacks physiological or prognostic validation. While our data support a continuous relationship between AA and procedural parameters without a clinically meaningful threshold, this does not entirely invalidate the clinical utility of dichotomization. Such binary definitions, despite their conceptual limitations, may still serve as practical tools for risk stratification and procedural planning, particularly in anatomically borderline or technically challenging cases. Our findings therefore suggest AA should ideally be assessed as a continuous variable but acknowledge that dichotomous thresholds may retain contextual value in everyday TAVI practice.

### Limitations

This study has several limitations that merit consideration. First, its retrospective and single-centre design introduces the potential for selection bias and limits the generalizability of the findings to broader populations or different institutional settings. Second, AA was defined solely based on a single, 2-dimensional measurement of AA derived from CT. While this definition is consistent with prior studies, it does not capture the full geometric complexity of the aortic root and delivery pathway. Important anatomical factors—such as aortic curvature, arch tortuosity, annular alignment, or device trajectory—were not assessed and may influence technical aspects of valve deployment. Third, the number of patients receiving SEV was relatively small, especially in brand-specific subgroup analyses, limiting statistical power to detect differences in device performance under challenging anatomical conditions. Moreover, extreme forms of horizontal angulation (e.g., ≥70°) were underrepresented, and conclusions cannot be extrapolated to such anatomies. Although the overall cohort was sizeable, some subgroup analyses may have lacked statistical power to detect subtle associations. Therefore, non-significant results with suggestive trends should be interpreted with caution. Finally, only transfemoral procedures using current-generation devices were included. As such, the findings cannot be generalized to earlier-generation devices, alternative access routes, or patients with prior valve interventions. Patients with bicuspid aortic valves were also excluded, as their distinct anatomical features—including asymmetrical calcification, elliptical annular configuration, and a propensity for more extreme angulation—differ substantially from tricuspid morphologies. Inclusion of such cases would have introduced significant anatomical heterogeneity and potentially confounded the isolated assessment of AA in a tricuspid setting.

## CONCLUSIONS

In this large, contemporary single-centre cohort, horizontal AA was independently associated with increased procedural imaging burden and resource utilization during transfemoral TAVI, evidenced by longer fluoroscopy times and higher contrast volume. However, an increased AA did not negatively impact device success, early safety, PVR, or the need for PPI. These findings were consistent across different transcatheter valve types.

## AUTHOR CONTRIBUTIONS

Emre Polat (Conceptualization, Investigation, Methodology, Project administration, Writing—original draft), Arianna Fortunato (Data curation, Investigation, Validation), Lena Schemet (Data curation, Investigation, Validation), Sarah Friedrich-Welz (Data curation, Investigation, Validation), Anton Tomsic (Data curation, Validation, Writing—review & editing), Mohamed Amer (Supervision, Validation, Writing—review & editing), Evaldas Girdauskas (Data curation, Investigation, Validation), and Tamer Owais (Data curation, Supervision, Validation)

## SUPPLEMENTARY MATERIAL

Supplementary material is available at *ICVTS* online.

## FUNDING

None declared.

## CONFLICTS OF INTEREST

None declared.

## DATA AVAILABILITY

Data are available in a repository and can be accessed via a DOI link.

## ETHICAL STATEMENT

Approved by the local Ethics Committee on March the 4th, 2024 (ID number 24-0028). Patient consent was waived because the study was conducted retrospectively using de-identified clinical and procedural data. No identifiable patient information was used, and the analysis did not influence or alter patient care.

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