Bicuspid aortic valve (BAV) is the most common congenital heart defect and has considerable morbidity and mortality. It occurs isolated or in combination with additional heart defects and may occur in the context of a syndrome. In young adults, valve dysfunction requiring an intervention occurs frequently and valve dysfunction degree seems associated to BAV morphologic phenotype. Aortic dilatation, predisposing for life-threatening rupture and dissection, is found in half of adult patients. Dilatation rates and its associations are well studied in adults, but for children these data are largely unclear. In children, the aortic diameter is typically corrected, mostly for body size area, age, and gender. The advised method is to use z-scores (the number of standard deviations above or below the expected diameter). Different regression equations for expected aortic diameter and corresponding z-scores are currently in use, none of which having emerged as optimal. In the present study, we retrospectively investigated aortic diameter (z-score) change during follow-up and its possible associations in a pediatric cohort with BAV.

Methods

We included all children <18 years diagnosed with a BAV, who underwent echocardiography between 2005 and 2013 in our center. Echocardiographic studies were performed by trained sonographers using GE Vivid 7, E9, or S6 and assessed in EchoPac PC 113 (GE Healthcare). Correct diagnosis and BAV morphology were determined by 2 independent researchers (EV, MS) in parasternal short-axis view. In 25 inconclusive cases, a third experienced cardiologist (ALD) had decisive judgment. Aortic diameters were measured if at least 1 echocardiographic study, accompanied by height and weight data, provided good view of the ascending aorta (AA) distal to the sinotubular junction (STJ). Exclusion criterion was valve replacement before start of the study.

We reviewed medical records for cardiac anomalies, syndromes, interventions, and valve dysfunction at included echocardiographies. Lesions presented together as Shone’s syndrome were scored separately for this study. Valve morphology was classified by the number of raphes...
Aortic valve regurgitation was present \( (V_{\text{max}}) \) Aortic valve stenosis (AS) was de
ular dimensions, and pressure half-time. Patients were descending aortic back
and Schmidtke,20 modified for echocardiography (Figure 1). Aortic valve stenosis (AS) was defined as a peak velocity \( (V_{\text{max}}) > 2.5 \text{ m/s}, \) as jet velocity is the strongest predictor for clinical outcome.21 Aortic valve regurgitation was present when reported mild or more, based on jet evaluation and descending aortic backflow on color Doppler, left ventric-
ular dimensions, and pressure half-time.22 Patients were scored as having hypertension when they were medically treated for high blood pressure.

One researcher (RM) measured aortic diameters at the sinus of valsalva (SOV), STJ, and AA, defined as maximal diameter between STJ and aortic arch. Up to 3 studies were included (oldest, latest, and middlemost; \( \geq \) 6 months apart). Measurements were performed in parasternal long-axis view at end-diastole, leading edge to leading edge, and perpen-
dicular to the long axis of the aorta (Supplementary Figure 1). Averages of 3 measurements, preferably in various cardiac cycles, were used. Missing height and weight data were interpolated if growth curves looked stable and had at least 4 points within 9 months.

Continuous variables are presented as mean (\( \pm \) SD) or median (interquartile range [IQR]) where appropriate, and categorical variables as frequencies. Differences were detected with Student’s \( t \), one-way analysis of variance, Pearson chi-square, Fisher’s exact, or McNemar tests. Intraclass correlation and Bland-Altman plots assessed interobserver agreement on aortic measurements between 2 observers in 20 random patients. Aortic diameters were converted to z-scores using 2 different methods: by Gautier et al and by Campens et al. Both used the body surface area
formula by Du Bois and both did not include neonates and toddlers,24,25 although, as representative data on these very young children are lacking, we nevertheless chose to apply these methods. For this reason, we also performed additional regression analysis on absolute diameters at first examination. A z-score \( > 2 \) was considered abnormal. Only Gautier’s method was used for analysis of aortic growth in various subgroups. To account for dependency of serial measurements, the mean z-score over time was described with 5th order polynomials (quintics) constructed from a linear mixed-effects model, allowing single and serial measurements, unequal intervals, and a random intercept per subject. A likelihood ratio test assessed differences between sub-
groups. This model only allowed a univariate approach. p-values \( < 0.05 \) were considered statistically significant. Analyses were performed in SPSS 20 (IBM Corp.).

Results
Of 11,792 children who underwent echocardiography, BAV was reported in 286. A total of 36 patients were excluded from the study because of incorrect diagnosis \( (n = 32) \), missing images \( (n = 1) \) or cardiac surgery distorting original valve anatomy before 2005 \( (n = 3) \). Of the 250 (2.1\%) remaining patients, aortic diameters could be assessed in 234 (Ross procedure after 2005, \( n = 1 \); image storage errors, \( n = 4 \); inadequate images, \( n = 7 \); no height or weight data, \( n = 4 \)), providing 580 studies. Table 1 de-
scribes their baseline characteristics, categorized by valve
placement. A likelihood ratio test assessed differences between sub-
groups. To account for dependency of serial measure-
ments, unequal intervals, and a random intercept per subject.

Interobserver agreement coefficients on aortic measure-
ments were 0.98 (SOV), 0.87 (STJ), and 0.96 (AA). Overall difference between observers was \( -0.39 \) mm \( (p < 0.01; \) Supplementary Figures 2 and 3). In 195 subjects, serial echocardiographic studies were available, with a median follow-up of 4.7 years \( (IQR 2.7 \) to 6.57). All ages were represented, with a slight overrepresentation of infants \( (Supplementary Figure 4). \) The median age at first examination was 6.1 years \( (IQR 1.7 \) to 10). During follow-up, 2 patients deceased (noncardiac death: 1 of hematologic and 1 of severe embryological disease) and 3 others underwent a Ross procedure for valve dysfunction, whereupon follow-up ended.

No aortic rupture, dissection, or preventive surgery was reported during follow-up. Mean z-scores and the prevalence of a z-score \( > 2 \) at first examination were highest for the AA (Table 2), irrespective of the used z-score equation.24,25 Figure 2 presents the 5th order polynomials best estimating the mean course of z-scores, with 95% confidence intervals of the estimate. The AA showed highest z-
scores and was the only location demonstrating significant growth between ages 5 and 15 years, for both z-score equations: 0.67 to 1.24 (Gautier) and 0.45 to 1.29 (Campens), resulting in mean growth rates of 0.06 and 0.09 z-score units per year, respectively. Both methods showed no z-score progression for the SOV. The STJ was significantly greater than normal, but also nonprogressive. Significant differences are observed between both methods of z-score equation, particularly in the neonatal and toddler ages, with exceedingly high z-scores for Campens’ equation.
For the SOV, a z-score $>2$ at inclusion ($p < 0.001$), male gender ($p < 0.01$), Sievers’ type 2 ($p < 0.01$), syndromes ($p < 0.001$), and absence of AS ($p < 0.05$) were associated with higher z-scores (Supplementary Figure 5). However, these factors were not independent: subjects with a syndrome more often had an initial z-score $>2$ (23% vs 6%, $p < 0.05$) and less often had AS (28% vs 60%, $p < 0.01$). Subjects with AS less often had an initial z-score $>2$ (4% vs 13%, $p < 0.05$). Higher STJ z-scores were observed in syndromes ($p < 0.05$), subjects with an initial z-score $>2$ ($p < 0.001$), and right-non coronary cusp fusion subtype within Sievers’ type 1 valve morphology ($p < 0.01$; Supplementary Figure 6), but again, they were nonprogressive.

**Discussion**

In this large population of children with BAV, we observed no rupture, dissection, or need for preventive aortic surgery. Only the AA z-score progressed with time, showing that the main emphasis on follow-up should lie on the aortic diameters at this location. An initial z-score $>2$
Table 2
Mean z-scores and prevalence of a z-score >2 at first echocardiography (n = 234, median age = 6.1 years)

<table>
<thead>
<tr>
<th></th>
<th>Gautier’s equation</th>
<th>Campens’ equation</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-score (mean ±SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinus of Valsalva</td>
<td>-0.2 ± 1.5</td>
<td>0.6 ± 1.5 †</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sinotubular junction</td>
<td>0.3 ± 1.8 †</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ascending aorta</td>
<td>0.8 ± 1.7 †</td>
<td>1.4 ± 2.2 †</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Z-score &gt;2 (% ±SE)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinus of Valsalva</td>
<td>8 ± 2</td>
<td>15 ± 2</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Sinotubular junction</td>
<td>15 ± 2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ascending aorta</td>
<td>24 ± 3</td>
<td>36 ± 3</td>
<td>&lt;0.001*</td>
</tr>
</tbody>
</table>

Significance compared with normal population (mean z-score = 0): †p <0.01; p <0.001.
Campens did not provide an equation for the sinotubular junction.
* McNemar test.

The AA shows the largest relative diameter and clearly grows faster than can be expected based on body growth and/or age. No significant differences in absolute AA diameter were observed between patients with isolated BAV and BAV patients with associated lesions or valve dysfunction. However, the isolated BAV group was only small. Although patients with an initial z-score >2 and patients with AS had a higher initial z-score, they all had similar AA growth, which makes AA diameter growth predictable. The progression of 0.06 to 0.09 z-score units per year was notably similar to literature that likewise used z-scores, as was absolute aortic diameter growth. Fernandes et al earlier concluded that young patients initially presenting with higher z-scores seem to be at highest risk for aortic dilatation at later age, and this seems valid for all locations. It seems logical that only the AA is at risk for dilatation-related complications, as it is the only location showing z-score progression, but whether these patients indeed have an elevated need to undergo (preventive) aortic surgery at later age is not well studied. We propose regular follow-up for patients entering young adulthood to overcome this gap in knowledge.

Earlier studies suggested protective effects of a coarctation history on AA z-score progression, but we could not confirm this finding. Also, aortic regurgitation and aortic or valvular interventions were not associated with aortic size. Previous studies reported conflicting data on the increase of aortic dimensions at the level of the SOV.8,10,17–19 We found no z-score progression at this level. The clinical relevance of having an underlying syndrome on STJ diameters remains unclear, mainly because of the heterogeneity of this group.

It is suggested that in adult cohorts, BAV morphology is associated with valve dysfunction and complications.4–6 Our study confirms this in a pediatric cohort. Valve morphology should be determined at young age, for which in our opinion Sievers’ classification is applicable. Distribution of BAV morphology differed from Sievers’ original study, possibly because of differences in age category.20 Comparing studies that included BAV morphology is challenging because of a large variety in classifications. Many studies applied morphologic classification named after localization of 1 supposed fusion line (right-left, right-non and left-non coronary cusp fusion), whereas Sievers’ classification also allows 0 and 2 fusion lines.5,8,9 Given the visual similarities between type 0 anteroposterior orientation and type 1 right-left coronary cusp fusion and between type 0 lateral orientation and type 1 right-left or left-non coronary cusp fusion (Figure 1), distribution of morphology, valve dysfunction, and interventions were notably similar to the literature.3,9

Z-score equation methods by Gautier et al and Campens et al regrettably are not designed for use in patients below 2 years, causing z-scores in these subjects to be only based on extrapolated data and difficult to interpret.22,26 Both methods provide clearly different results in this age group, with Campens’ method appearing the least accurate. For this reason, we calculated the annual z-score progression in children between 5 and 15 years. As we clinically found children presenting with AA z-scores >2 to have larger AAs in adolescence, we urge the need for z-score validation in

and presence of AS were clinical markers for higher z-scores in early adulthood, but z-score progression was not faster. Indeed, aortic pathology in the context of BAV seems not a clinical problem in childhood. Previous studies compared contributing factors using numerical growth rates. This is the first study providing a visualized comparison of aortic diameter growth in children with a BAV.8,10,17–19

As expected, BAV was common in our pediatric cardiology department and clearly associated with valve- and non-valve-related morbidity such as coarctation of the aorta, but also with other anomalies such as ventricular septal defects and patent ductus arteriosus, for which only putative associations were mentioned.5–7,27–29 Awareness and echocardiographic screening for other anomalies in clinical practice is mandatory. Similar to Fernandes et al,9 valve interventions occurred in a minority and mainly early in life, typically for aortic stenosis. Most importantly, no intervention for aortic dilatation was needed and no complications of aortic dilatation occurred. However, some follow-up seems warranted as we do not want to miss the individual patient with rapid increase in diameter. For the patient with isolated, normally functioning BAV, we suggest to perform echocardiography every 5–10 years.
cohorts with sufficient representation of neonates and toddlers, for the clinician to be aware of the expected growth. Instead of using the z-score, we propose to use Figure 3 to evaluate whether a specific AA diameter is abnormal for a child with a BAV and possibly associated with complications later in life. This could be of benefit especially in patients younger than 5 years of age as the z-score has clear limitations here. Patients with an AA diameter above the 95% prediction interval of our BAV cohort should therefore probably be controlled more frequently.

All limitations of a retrospective study apply. We studied subjects in our tertiary center, introducing a selection bias. Two-dimensional echocardiography might not represent the 3-dimensional aortic shape and might have been subject to technical improvement during the study. We nonetheless believe in the reproducibility of this study with high interobserver agreement and observed differences within reported measurement variability.23 Echocardiography is still the primary investigation of choice for diagnosis and follow-up of children with a BAV, making our results applicable to most clinical situations. Our predictions lack external validation and we hope other research groups will provide this in the near future. The elementary shape of a 5th order polynomial might influence results in the extreme ages, although accuracy is suggested by the population size.

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Disclosures

The authors have no conflicts of interest to disclose.

Supplementary Data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.amjcard.2017.03.245.


