Original Article

Aortic valve leaflet and root dimensions in normal tricuspid aortic valves: A computed tomography study

Matija Jelenc MD, PhD1 | Blaž Jelenc PhD2 | Gregor Poglajen MD, PhD3,4 | Nikola Lakič MD, PhD1

1Department for Cardiovascular Surgery, University Medical Center Ljubljana, Ljubljana, Slovenia
2Department of Mathematics, Faculty of Mathematics and Physics, University of Ljubljana, 1000, Osrednjeslovenska, Ljubljana, Slovenia
3Advanced Heart Failure and Transplantation Program, Department of Cardiology, University Medical Center Ljubljana, Ljubljana, Slovenia
4Department of Internal Medicine, Faculty of Medicine, University of Ljubljana, Ljubljana, Slovenia

Correspondence
Matija Jelenc, MD, PhD, Department for Cardiovascular Surgery, University Medical Center Ljubljana, Zaloška 7, 1000 Ljubljana, Slovenia.
Email: jelenc@gmail.com

Funding information
University Medical Center Ljubljana

Abstract

Background and Aim of the Study: The aim of this study was to use coronary computed tomography in patients with normal tricuspid aortic valves to perform detailed aortic root and aortic valve geometric analysis with a focus on the asymmetry of the three leaflets.

Methods: Retrospective analysis of anonymized coronary computed tomography angiograms was performed using dedicated software, where manual aortic root segmentation and marking of several points of interest were followed by automated measurements of aortic root and leaflets. Asymmetry of the three leaflets in individual patients was assessed by calculating absolute and relative differences between the largest and the smallest of the three leaflets.

Results: We analyzed 70 aortic valves, the mean patient age was 53 ± 11 years, and 50% (n = 35) of patients were female. All aortic valves were tricuspid, without calcifications and aortic roots were of normal dimensions. Some degree of asymmetry was present in all analyzed valves. Absolute and relative differences for free margin length were 3.2 ± 1.4 mm and 9.3 ± 3.8%, respectively. The largest relative difference was noted in the coaptation area (36.5 ± 16.5%) and the smallest in leaflet effective height (6.1 ± 4.8%). Using predefined cutoff criteria for absolute differences in leaflet dimensions, 86% of the valves were classified as asymmetric.

Conclusions: Most normal tricuspid aortic valves show some degree of asymmetry. Equal free margin length of the three leaflets is not needed for normal tricuspid aortic valve function. Leaflet effective height showed the least amount of asymmetry confirming its importance in keeping the aortic valve competent.

Keywords
3D modelling, aortic valve anatomy, aortic valve repair, computed tomography

Abstract of preliminary results of this study was presented at 34th EACTS annual meeting in Barcelona 2020.

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INTRODUCTION

Clinical experience shows that tricuspid aortic valves can be very asymmetric in terms of leaflet size and free margin length but still function normally. In tricuspid aortic valves, equal effective leaflet height appears to be more important than equal free margin length. The primary aim of the present study was to use coronary computed tomography angiography (CTA) in patients with normal tricuspid aortic valves to perform detailed aortic root and aortic valve geometric analysis with a focus on the asymmetry of the three leaflets.

MATERIALS AND METHODS

2.1 Study design

We retrospectively analyzed 127 anonymized coronary CTAs performed between March 2017 and December 2021 that were chosen randomly from our hospital’s picture archiving and communication system. The anonymized CTAs included gender, age, height, and weight of the patient in the metadata.

2.2 Ethics

The study was approved by the National Medical Ethics Committee (NMEC; Komisija Republike Slovenije za medicinsko etiko, No. 0120-133/2021/3, May 14, 2021). Written patient informed consent was waived by NMEC as this was a noninterventional study.

2.3 Inclusion and exclusion criteria

Fifty-seven CTAs were excluded from further analysis due to one or more of the following reasons: bicuspid aortic valve, poor contrast, poor leaflet visibility, motion artefacts, calcifications of aortic valve leaflets, and diameter of sinuses of Valsalva ≥45 mm. On the remaining 70 CTAs, all aortic valves were tricuspid, without calcifications, with no visible coaptation defects, and the diameter of the sinuses of Valsalva was <45 mm. On the basis of the morphology of leaflets and absence of calcification and coaptation defects, we assumed all analyzed aortic valves functioned normally, however this was not confirmed by echocardiography.

2.4 Valve analysis

All valve analyses were performed in the end-diastolic phase of the cardiac cycle. The CTAs were imported into Mimics Innovation Suite v. 21.0 (Materialise) where aortic roots were segmented. Several geometric points of interest (Figure 1) were marked on each segmented aortic root in a three-dimensional (3D) space. Spline tool was used to define coaptation surfaces, leaflet attachments, commissural heights, and annular and sinutubular perimeters for each patient. The diameter of the sinuses of Valsalva was measured using the maximal internal distance between the farthest points on the right and the noncoronary sinuses of Valsalva (“cusp-to-cusp”) in a plane parallel to the annular plane. The points and splines defined by 3D coordinates were then imported into Mathematica v12.0 (Wolfram Research) where dedicated code was used to reconstruct the aortic valve in 3D space from the measured points and splines, define different planes, calculate relevant angles, lengths, and areas for each patient. The central coaptation point was calculated as a mean of the tips of the three geometric height splines.

Asymmetry of the three leaflets in individual patients was assessed by calculating absolute and relative differences. The absolute difference for selected measurement was defined as the difference between the largest and the smallest of the three leaflets. The relative difference for selected measurement was defined as the absolute difference divided by the mean of the three leaflets.

![Figure 1](image-url) (A) The lowest points of leaflet attachments in the nadirs of sinuses of Valsalva (R, L, N) were marked on the segmented aortic root and were used to define the annular plane. The highest points of the three commissures were also marked and used to define the sinutubular plane. Next spline tool was used to trace leaflet attachment lines, geometric heights, annular and sinutubular perimeters, and leaflet coaptation areas. (B) Example of geometric height (GH) and coaptation area (CA) measurement on CTA. CTA, computed tomography angiography; L, left; N, noncoronary; R, right.
2.5 | Statistical methods

Statistical data analysis was performed using JASP v 0.14.1 (University of Amsterdam, Netherlands). The normal distribution of variables was assessed using the Shapiro–Wilk test. Continuous variables are reported as mean ± standard deviation. Differences were analyzed using independent samples t-test and repeated measures analysis of variance with post hoc test with Bonferroni correction. Correlations were assessed using Pearson’s correlation coefficient. In an analysis of asymmetry, one sample t-test and Wilcoxon signed-rank test were used. p < .05 was considered statistically significant.

3 | RESULTS

Baseline patient and aortic valve data are presented in Tables 1 and 2 and are graphically summarized in Figures 2 and 3, where measurements are normalized to either annular mean diameter to allow comparison to data published by Swanson and Clark6 or to mean leaflet geometric height to allow comparison to data published by De Kerchove et al.6

The mean age of patients was 53 ± 11 years, with no difference between men and women (Table 1). 50% of patients (n = 35) were female. Men were higher and heavier, with larger aortic roots (larger annular diameter, sinutubular junction diameter, sinuses of Valsalva diameter, and all leaflet dimensions); however, the geometry of aortic root and leaflets was similar (all angles, as well as normalized dimensions, were similar) (Supporting Information: Table 1). Similarly, body surface area, aortic root dimensions, and leaflet dimensions were all positively correlated (Figure 4); however, normalized root and leaflet dimensions, as well as angles, showed no correlation with body surface area, implying that the shape and proportions of the aortic root and leaflets were similar in large and small patients.

The right coronary leaflet had the longest mean free margin length (35.2 ± 4.1 mm) and intercommissural distance (25.1 ± 3.0 mm), whereas the noncoronary leaflet had the longest mean geometric height (16.5 ± 2.0 mm) and leaflet attachment length (51.7 ± 6.6 mm). Right-noncoronary commissure was the highest of the three (20.6 ± 3.0 mm). Mean free margin length was almost identical (34.0 ± 4.0 mm in our study vs. 34.4 ± 3.1 mm), longest in the right aortic leaflet and shortest in the left aortic leaflet. A similar relationship was found in intercommissural distances. Mean geometric leaflet height was shorter in our study (15.9 ± 1.6 vs. 18.9 ± 1.5 mm), with both studies showing the longest geometric height in the noncoronary leaflets, similar to the study by Schafer et al.7 The reason for this difference may be different body size of patients and different methodology of measurement. In a Japanese study9 with a similar methodology mean geometric height was 14.7 mm with a mean body surface area of 1.7 m², whereas the mean body surface area in our study was 1.9 m². On CTA, geometric height is measured in diastole with the aortic valve closed, whereas in homografts or intraoperatively, the leaflet is placed under tension during geometric height measurement. A difference of 1.8 mm after preoperative CTA and intraoperative measurements of geometric size was found in a study by Komiya et al.9 Longer intraoperative geometric leaflet height was also found in a study by Schäfers et al.7; however, some of the differences may be attributed to the fact that measurements were performed on patients with aortic valve and root pathology, where leaflet distension may occur.10 Coaptation surfaces were larger in our study, with the largest surface on the right coronary leaflet, a finding similar to De Kerchove et al.6 However, as coaptation surface is often difficult to delineate on CTA as it may not lie in a single plane, this

4 | DISCUSSION

There are several advantages of using coronary CTA in morphologic aortic valve analysis. Aortic valves are observed in vivo in diastole, pressurized with physiologic diastolic pressure with all the surrounding structures intact. Unlike in anatomical studies where tissues are fixed with glutaraldehyde,5,6 the mechanical properties of leaflets and roots in our study were not altered. Measurements performed on the segmented root in 3D space allow the definition of different points, lines, planes, angles, and relationships, some of which cannot be done on anatomical models.

The patients in our study had normal tricuspid aortic valves and normal root dimensions as in the study on homografts by De Kerchove et al.6 In both studies, the right-noncoronary commissure was the highest (20.6 ± 3.0 mm in our study vs. 21.8 ± 2.1 mm). Mean free margin length was almost identical (34.0 ± 4.0 mm in our study vs. 34.4 ± 3.1 mm), longest in the right aortic leaflet and shortest in the left aortic leaflet. A similar relationship was found in intercommissural distances. Mean geometric leaflet height was shorter in our study (15.9 ± 1.6 vs. 18.9 ± 1.5 mm), with both studies showing the longest geometric height in the noncoronary leaflets, similar to the study by Schäfers et al.7 The reason for this difference may be different body size of patients and different methodology of measurement. In a Japanese study9 with a similar methodology mean geometric height was 14.7 mm with a mean body surface area of 1.7 m², whereas the mean body surface area in our study was 1.9 m². On CTA, geometric height is measured in diastole with the aortic valve closed, whereas in homografts or intraoperatively, the leaflet is placed under tension during geometric height measurement. A difference of 1.8 mm after preoperative CTA and intraoperative measurements of geometric size was found in a study by Komiya et al.9 Longer intraoperative geometric leaflet height was also found in a study by Schäfers et al.7; however, some of the differences may be attributed to the fact that measurements were performed on patients with aortic valve and root pathology, where leaflet distension may occur.10 Coaptation surfaces were larger in our study, with the largest surface on the right coronary leaflet, a finding similar to De Kerchove et al.6 However, as coaptation surface is often difficult to delineate on CTA as it may not lie in a single plane, this
| Parameters                                                                 | Values     | Range      | Groups     | p         |
|---------------------------------------------------------------------------|------------|------------|------------|-----------|
| Age (years), mean ± SD                                                   | 53 ± 11    | 27–83      | M versus F | .225*     |
| Male gender, n (%)                                                       | 35 (50%)   |            |            |           |
| Weight (kg), mean ± SD                                                   | 76 ± 15    | 50–108     | M versus F | .001*     |
| Height (cm), mean ± SD                                                   | 172 ± 9    | 154–193    | M versus F | .001*     |
| Body surface area \( m^2 \), mean ± SD                                  | 1.91 ± 0.24| 1.49–2.43  | M versus F | .001*     |
| Annular diameter – perimeter based (mm), mean ± SD                       | 24.7 ± 2.6 | 19.5–31.2  | M versus F | .001*     |
| Sinutubular junction diameter (mm), mean ± SD                           | 27.8 ± 3.1 | 21.9–37.9  | M versus F | .001*     |
| Sinuses of Valsalva diameter (mm), mean ± SD                            | 34.3 ± 4.0 | 26.4–43.5  | M versus F | .001*     |
| Commissural height (mm), mean ± SD                                       | 19.3 ± 2.3 | 13.6–29.2  |             | .001**    |
| R/L commissure                                                           | 18.8 ± 2.0 | 14.5–28.8  | R/L versus L/N | .550*** |
| L/N commissure                                                           | 18.4 ± 2.4 | 13.6–24.4  | R/L versus R/N | .001*** |
| R/N commissure                                                           | 20.6 ± 3.0 | 15.3–29.2  | L/N versus R/N | .001*** |
| Intercommissural distance (mm), mean ± SD                                | 24.0 ± 2.6 | 18.5–32.8  |             | .001**    |
| Right leaflet                                                            | 25.1 ± 3.0 | 19.0–34.6  | R versus L | .001***   |
| Left leaflet                                                             | 23.3 ± 2.6 | 18.5–32.8  | L versus N | .105***   |
| Noncoronary leaflet                                                      | 23.7 ± 2.7 | 19.0–30.8  | R versus N | .001***   |
| Leaflet attachment length (mm), mean ± SD                                | 51.2 ± 5.8 | 39.2–68.4  |             | .001**    |
| Right leaflet                                                            | 51.6 ± 6.0 | 40.0–66.2  | R versus L | .001***   |
| Left leaflet                                                             | 50.0 ± 5.6 | 39.2–63.8  | L versus N | .001***   |
| Noncoronary leaflet                                                      | 51.7 ± 6.6 | 41.6–68.4  | R versus N | 1.000***  |
| Free margin length (mm), mean ± SD                                       | 34.0 ± 4.0 | 25.8–47.8  |             | .001**    |
| Right leaflet                                                            | 35.2 ± 4.1 | 27.6–46.4  | R versus L | .001***   |
| Left leaflet                                                             | 32.6 ± 3.8 | 25.8–43.7  | L versus N | .001***   |
| Noncoronary leaflet                                                      | 34.2 ± 4.3 | 26.4–47.8  | R versus N | .001***   |
| Valve height (mm), mean ± SD                                             | 19.2 ± 2.2 | 14.9–24.4  | M versus F | .001*     |
| Geometric height (mm), mean ± SD                                         | 15.9 ± 1.6 | 10.5–21.1  |             | .001**    |
| Right leaflet                                                            | 15.2 ± 1.9 | 10.5–19.3  | R versus L | .001***   |
| Left leaflet                                                             | 16.2 ± 1.8 | 12.1–19.8  | L versus N | .636***   |
| Noncoronary leaflet                                                      | 16.5 ± 2.0 | 12.0–21.1  | R versus N | .001***   |
| Coaptation area between two adjacent leaflets \( mm^2 \), mean ± SD       | 82 ± 18    | 39–166     |             | .001**    |
| R/L coaptation area                                                      | 79 ± 19    | 42–136     | R/L versus L/N | .001*** |
| L/N coaptation area                                                      | 71 ± 18    | 39–128     | R/L versus R/N | .001*** |
| R/N coaptation area                                                      | 97 ± 24    | 58–166     | L/N versus R/N | .001*** |
| Central coaptation length (mm), mean ± SD                                | 3.7 ± 0.6  | 2.3–5.5    | M versus F | .420*     |
| Effective height (mm), mean ± SD                                         | 8.5 ± 1.4  | 4.8–14.0   |             | .388**    |
| Right leaflet                                                            | 8.5 ± 1.6  | 4.8–14.0   | R versus L | 1.000***  |
| Left leaflet                                                             | 8.5 ± 1.4  | 4.8–11.5   | L versus N | .558***   |

(Continues)
TABLE 1  (Continued)

| Parameters | Values | Range | Groups | p       |
|------------|--------|-------|--------|---------|
| Noncoronary leaflet | 8.4 ± 1.4 | 5.0–11.6 | R versus N | .972*** |
| Distance between central coaptation point and annular plane relative to valve height, mean ± SD | 0.46 ± 0.07 | 0.27–0.68 | M versus F | .433*** |

Abbreviations: ANOVA, analysis of variance; F, female; L, left; M, male; N, noncoronary; R, right.

*Mosteller formula was used to calculate body surface area.

*Independent samples t-test.

**Repeated measures ANOVA.

***Post hoc test with Bonferroni correction.

TABLE 2  Aortic valve angles.

| Parameters | Values | Range | Groups | p       |
|------------|--------|-------|--------|---------|
| Leaflet belly to annular plane angle (°), mean ± SD | 24.2 ± 5.8 | 8.0–37.0 |        | <.001*  |
| Right leaflet | 26.8 ± 7.1 | 9.1–43.1 | R versus L | <.001** |
| Left leaflet | 23.5 ± 5.4 | 10.2–33.4 | L versus N | .229**  |
| Noncoronary leaflet | 22.4 ± 6.7 | 8.0–37.0 | R versus N | <.001** |
| Free margin to sinutubular plane angle (°), mean ± SD | 36.8 ± 4.9 | 21.0–45.8 |        | <.001    |
| R/L commissure | 37.1 ± 6.0 | 22.5–48.2 | R/L versus L/N | <.001** |
| R/N commissure | 33.6 ± 5.0 | 18.3–45.2 | R/L versus R/N | <.001** |
| L/N commissure | 39.2 ± 5.1 | 22.4–50.0 | L/N versus R/N | <.001** |
| Angle occupied by individual leaflet relative to sinutubular plane (°), mean ± SD | 120 ± 6 | 104–141 |        | <.001*  |
| Right leaflet | 122 ± 5 | 109–141 | R versus L | 1.000** |
| Left leaflet | 122 ± 5 | 109–134 | L versus N | <.001** |
| Noncoronary leaflet | 116 ± 6 | 104–135 | R versus N | <.001** |
| Sinutubular to annular plane angle (°), mean ± SD | 7.8 ± 3.9 | 0.7–22.7 | M versus F | <.001*** |

Abbreviations: ANOVA, analysis of variance; F, female; L, left; M, male; N, noncoronary; R, right.

*Repeated measures ANOVA.

**Post hoc test with Bonferroni correction.

***Independent samples t-test.

FIGURE 2  Graphical summary of measured aortic valve data. (A) Mean coaptation surface between two adjacent leaflets of 82 mm². Mean free margin to sinutubular plane angle of 37°, mean leaflet belly to the annular plane of 24°, and mean angle between sinutubular and annular planes of 8°. (B) Angles occupied by individual leaflets relative to sinutubular plane (left 122°, right 122° and noncoronary 116°). Also, note the relative heights of commissures, with RN commissure being the highest. LN, left noncoronary; RL, right and left coronary leaflet; RN, right noncoronary.
measurement should be interpreted carefully as it is prone to error. Central coaptation length was also similar (3.7 ± 0.6 mm in our study vs. 3.3 ± 0.8 mm). When normalized to the geometric height we found all dimensions longer than the data published by De Kerchove et al.,⁶ which probably reflects the relatively shorter mean geometric height.

Normalizing root and leaflet dimensions to annulus diameter gave results comparable to the study by Swanson and Clark.⁵ Some dimensions such as geometric height and central coaptation length were somewhat smaller; however, normalized sinutubular diameter was larger (1.13 vs. 1.0) and one-half of free margin length was longer.
Leaflet belly to annulus angle was similar (24° vs. 22°) as well as the free margin to sinutubular plane angle (37° vs. 32°). One explanation could be the higher age of our patients (53 ± 11 vs. 35 ± 6 years) causing the increase in sinutubular junction diameter and longer free margin length.

All aortic valves displayed some degree of asymmetry. Absolute differences between the three leaflets of individual patients were very similar to data published by De Kerchove et al.6 Absolute difference in free margin length 3.2 ± 1.4 versus 3.1 ± 1.4 mm, in intercommissural distance 2.6 ± 1.1 versus 3.6 ± 1.7 mm, in geometric height 2.5 ± 1.3 versus 1.9 ± 1.0 mm, and in leaflet attachment length 4.0 ± 2.1 versus 5.0 ± 2.3 mm. Using predefined cutoff values for absolute differences in leaflet dimensions and observing a single leaflet dimension at once, on average 42% of valves in our study were classified as asymmetric, whereas approximately 54% were asymmetric in the study by De Kerchove et al.6 However when observing all four leaflet dimensions at once, 86% of valves were asymmetric in at least one of the four selected dimensions.

Another limitation is the lack of echocardiographic control of the valves we studied, which was not possible due to the study design.

### Table 3

| Leaflet dimension                        | Absolute difference ± SD (range) | Relative difference ± SD (range) |
|------------------------------------------|----------------------------------|----------------------------------|
| Leaflet attachment length (mm)           | 4.0 ± 2.1 (0.4–10.8)             | 7.7 ± 3.8 (0.8–19.2)             |
| Geometric height (mm)                    | 2.5 ± 1.3 (0.4–6.0)              | 16.0 ± 8.2 (2.3–40.9)            |
| Effective height (mm)                    | 0.5 ± 0.5 (0.0–2.9)              | 6.1 ± 4.8 (0.1–23.7)             |
| Free margin length (mm)                  | 3.2 ± 1.4 (0.4–6.6)              | 9.3 ± 3.8 (1.3–18.9)             |
| Coaptation area between two adjacent leaflets (mm²) | 30.1 ± 14.9 (0.5–76.2)           | 36.5 ± 16.5 (0.7–97.7)           |
| Commissural height (mm)                  | 2.9 ± 1.7 (0.4–8.6)              | 15.0 ± 8.0 (2.3–47.0)            |
| Intercommissural distance (mm)           | 2.6 ± 1.1 (0.2–6.3)              | 10.8 ± 3.8 (1.0–23.0)            |
| Leaflet belly to annular plane angle (°) | 6.9 ± 3.7 (0.9–17.3)             | 29.2 ± 15.2 (4.5–68.0)           |
| Free margin to sinutubular plane angle (°) | 6.9 ± 2.8 (0.4–13.8)          | 19.0 ± 7.5 (1.1–36.9)            |
| Angle occupied by individual leaflet relative to sinutubular plane (°) | 12.3 ± 6.7 (1.3–34.4)         | 10.3 ± 5.6 (1.1–28.7)            |

### Table 4

| Leaflet dimension                        | Absolute difference criteria for symmetry | N (%) of asymmetric valves |
|------------------------------------------|-------------------------------------------|----------------------------|
| Free margin length                       | <3 mm                                      | 34 (49%)                   |
| Geometric height                         | <2 mm                                      | 40 (57%)                   |
| Intercommissural distance                | <3 mm                                      | 22 (31%)                   |
| Leaflet attachment length                | <5 mm                                      | 21 (30%)                   |

4.1 Limitations

The main limitations of CTA were contrast and resolution. Ideally, there was a lot of contrast in the aorta and left ventricle but much less in the right side of the heart and pulmonary circulation. In these cases, the aortic root segmentation was fast and straightforward. When this was not the case, segmentation was prolonged because the structures surrounding the root needed to be removed manually.

The second issue was the visibility of aortic leaflets. Particularly in young patients, the leaflets are normally very thin and may not be clearly visible on CTA. Consequently, the least reliable measurement in our study was the coaptation areas between the leaflets, which may not even lie in a single plane and are sometimes difficult to visualize.

Another limitation is the lack of echocardiographic control of the valves we studied, which was not possible due to the study design.
Therefore, we only assumed valve function was normally based on their morphology, absence of calcification, and absence of coaptation defects.

Detailed measurements of sinuses of Valsalva were not included in our study dataset, although they have an important role in aortic valve closure and opening and sharing the stress with aortic valve leaflets.13–15

5 | CONCLUSION

Asymmetry in tricuspid aortic valves is normal and was present in all valves we analyzed. Using cutoff criteria for absolute differences in leaflet dimensions, 86% of the valves were classified as asymmetric.

Equal free margin length of the three leaflets is not needed for normal tricuspid aortic valve function. Aligning the leaflet free margin length in standardized aortic valve repair16,17 serves to match the halves of opposing leaflet pairs, thereby guiding in a semiquantitative way the amount of plication needed to treat prolapse, but it does not make the free margin lengths equal. Leaflet plication is then further fine-tuned to equalize effective leaflet height, which seems to be the least variable and most important parameter for the competency of tricuspid aortic valves.

Respecting asymmetry when performing reimplantation or remodeling procedures in very asymmetric cases is mandatory, whereas in less asymmetric cases, it may reduce the need for leaflet plication.

AUTHOR CONTRIBUTIONS
Matija Jelenc: Conceptualization, data curation, funding acquisition, methodology, software, and writing – original draft. Blaž Jelenc: Data curation, formal analysis, methodology, software, and visualization. Gregor Poglajen: Formal analysis, supervision, validation, and writing – review and editing. Nikola Lakič: Funding acquisition, methodology, project administration, resources, supervision, and writing – review and editing.

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CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

ORCID
Matija Jelenc http://orcid.org/0000-0003-2318-5709

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SUPPORTING INFORMATION
Additional supporting information can be found online in the Supporting Information section at the end of this article.

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