Spatial relationship between the pulmonary trunk and the left coronaries: Systematic risk assessment based on automated three-dimensional distance measurements

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BACKGROUND Catheter ablation of right ventricular outflow tract ventricular arrhythmias from above the pulmonary valve is being increasingly reported.

OBJECTIVE The purpose of this study was to systematically analyze the spatial relationship between the pulmonary trunk and the left coronaries.

METHODS Contrast-enhanced computed tomographic scans from 58 patients were analyzed. After segmentation of the pulmonary trunk and the proximal left coronaries, 3-dimensional geometries were generated. Minimal distance between the pulmonary trunk and the coronaries was automatically determined using a newly developed mathematical algorithm.

RESULTS The minimal distance between the pulmonary trunk and the coronaries was 1.4 ± 0.11 mm. Closest relationship was detected 13.8 ± 0.87 mm above the pulmonary valve annulus. Considering a safety margin of 5 mm to render coronary damage unlikely, 84% of patients were found to be at potential risk within the bottom 10 mm of the left sinus cusp. In contrast, positions within or above the right and anterior cusps were less likely to exhibit a close relationship. We identified the anterior aspect of the left cusp as the most critical region. Positions 10–20 mm above the left cusp were found to be critical in 97% of patients. Clinical parameters such as gender, age, height, weight, and body mass index were not predictive of a close spatial relationship.

CONCLUSION Our data provide evidence for a close spatial relationship between the pulmonary trunk and coronary arteries. These results should be considered when performing catheter ablation from above the pulmonary valve.

KEYWORDS Catheter ablation; Coronary arteries; Coronary damage; Pulmonary sinus cusps; Pulmonary trunk; Right ventricular outflow tract; Risk assessment; Spatial relationship; Ventricular arrhythmias

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Introduction

Ventricular arrhythmias (VAs) arising from the right ventricular outflow tract (RVOT) are a common finding in clinical practice. Current guidelines indicate catheter ablation in symptomatic patients or in those with high arrhythmia burden.[1,2] In the past, catheter ablation has been restricted to the myocardium just below the pulmonary valve. However, it is well recognized that this approach might not be successful in abolishing RVOT arrhythmias in some selected cases. One reason might be an ablation target located within musculature sleeves that extend several millimeters above the pulmonary valve into the pulmonary trunk.[3,4] Recently, a

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KEY FINDINGS

- There is a close spatial relationship between the pulmonary trunk and the coronary system. Whereas the right coronary artery passes within a safe distance (>10 mm) in patients without coronary anomalies, the distance to the proximal part of the left coronaries seems critical.
- More than 80% of patients exhibit a minimal distance below 5 mm between the pulmonary trunk and the proximal part of the left coronaries. Critical regions include the left pulmonary cusp, parts of the anterior cusp, and an area 10–20 mm above the left pulmonary cusp.
- Clinical data, such as gender, age, weight, height, and body mass index, do not help identify patients at increased risk. To avoid coronary damage, simultaneous coronary angiography should be considered when ablating within critical regions.

novel technique that approaches ablation targets from above the pulmonary valve using a reversed U-curve has been described.[5–7] Catheter ablation within the pulmonary trunk seems to further increase the success rates of catheter ablation of RVOT-VAs. However, it is well recognized that these ablation sites can be located close to the proximal part of the left coronaries.[8–10] Considering that catheter ablation can result in acute coronary damage or even coronary occlusion,[11] detailed information about this spatial relationship is crucial. As a consequence, simultaneous coronary angiography is being performed routinely at our center when ablating within or above the anterior or left pulmonary sinus cusp (LPSC). In a few cases, we decided against energy delivery due to safety concerns. However, this approach is center-specific and might not be representative. For example, Zhang et al[6] performed successful ablation of RVOT-VAs from above the pulmonary valve in 81 patients. In their study, systematic exclusion of a close spatial relationship between the ablation site and the coronary arteries was not reported.[6] Taken together, the close anatomic relationship between ablation sites within the pulmonary trunk and the coronary arteries is of great clinical importance.[9,10] However, systematic analysis of the complex anatomic situation has not yet been performed. The purpose of this study was to systematically analyze the exact anatomic relationship between the entire pulmonary trunk and the proximal left coronaries using a newly developed automated algorithm that allows precise distance measurements within 3-dimensional geometries.

Methods

Patient selection

All patients who had undergone a triple-ruleout computed tomographic (CT) scan between August 2014 and March 2018 at our center were screened for possible inclusion in this retrospective study. All patients gave informed consent. A total of 157 patients could be identified. Individuals who exhibited significant calcification or stenosis of the proximal left coronary arteries, low overall image quality, or missing clinical data were excluded. Clinical and imaging data from the remaining 58 patients were subject to further analysis. No coronary anomalies of the left coronaries were present in the patients in this study. The study design was approved by the ethics committee of the University of Heidelberg (S-601/2018) and conformed to the standards defined in the Helsinki Declaration (64th version, Fortaleza, Brazil, 2013).

Manual segmentation and generation of 3-dimensional models

Patients received up to 40 mg metoprolol tartrate intravenously and 2 sprays of nitroglycerin sublingually before triple-ruleout CT scan was performed. Up to February 2018, triple-ruleout CT scans were performed using a 256-slice CT scanner (Brilliance iCT; Philips Healthcare, Cleveland, OH) with the following parameters: helical mode, tube voltage 100 kV, slice thickness 0.8 mm, and field of view 317 mm. After February 2018, CTs were performed using a dual-layer spectral detector CT (IQon Spectral CT, Philips Healthcare) with the following parameters: helical mode, tube voltage 120 kV, slice thickness 0.7 mm, and field of view 220 mm.

All CTs were prospectively electrocardiography-gated from the aortic arch below the inferior border of the heart with image reconstruction at 75% of the R-R interval during a single breath-hold. Iomeprol (400 mg iodine/mL) 80-mL bolus at 4.5 mL/s was injected intravenously, followed by a flush of saline.

Reconstruction and analysis of CT data were performed using the IntelliSpace software module (Philips GmbH, Hamburg, Germany). The built-in automated segmentation tool (EP planning) was applied for a first approximate segmentation of the cardiac cavities. Detailed segmentation, especially within the pulmonary sinus cusps, was then performed using the spherical eraser and manual injection of virtual contrast agent. Coronary arteries were segmented manually using virtual injection of contrast agent (Figures 1A and 1B). Segmentation of the left coronaries was started at the aortic root and continued following the left main and left anterior descending arteries until the proximity to the pulmonary trunk and right outflow tract decreased markedly. Septal branches as well as the left circumflex artery were excluded. Depending on the individual anatomic situation, closest proximity could involve either the left main or the left anterior descending artery. Segmentation of the right coronary artery also started at the aortic root and continued until the proximity to the pulmonary trunk decreased markedly. For all anatomic structures, careful attention was paid to strictly adhere to the blood–tissue interface as marked by radiographic contrast agent. Three-dimensional models of all anatomic structures based on automated volume rendering

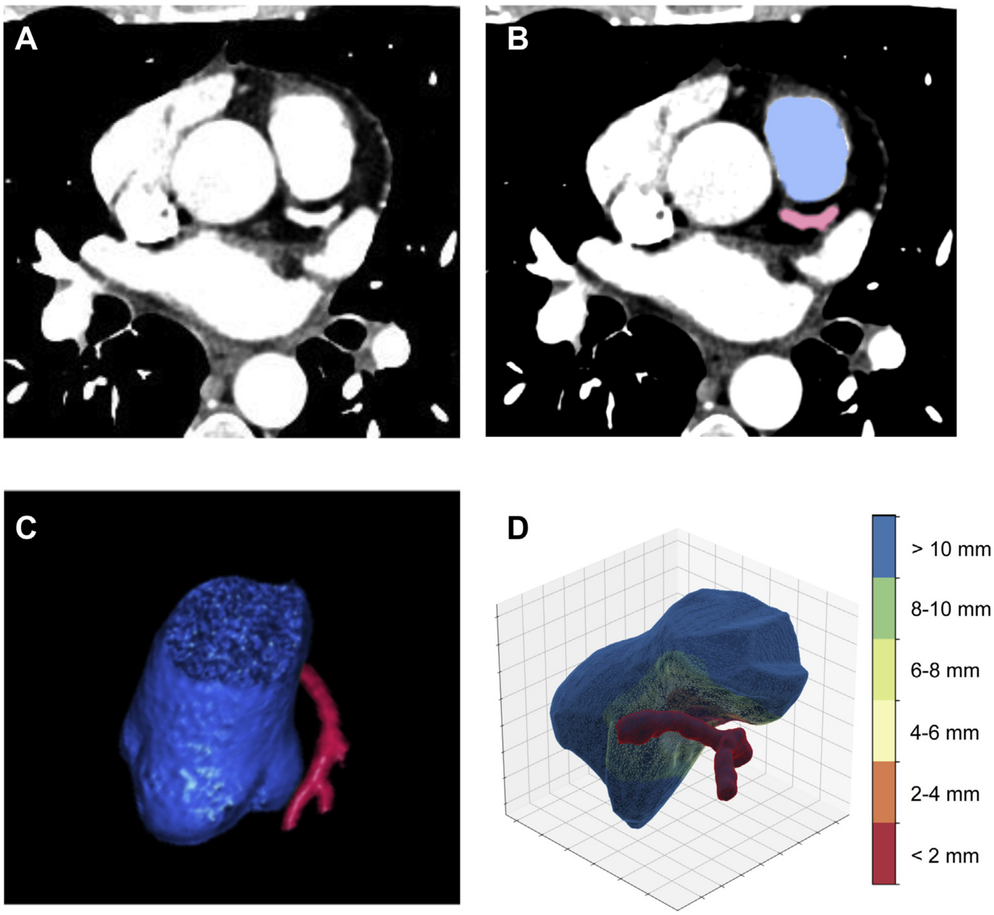

Figure 1 Generation of 3-dimensional anatomic models. Based on contrast-enhanced computed tomographic images **(A),** the proximal part of the pulmonary trunk and the left coronaries was carefully segmented **(B). C:** Three-dimensional models based on volume rendering were then transferred to a newly developed software tool in order to automatically determine the minimal distance to the coronaries. **D:** The close spatial relationship is demonstrated exemplarily with *red* marking areas of minimal distance and *blue* marking areas of wide distance.

(Figure 1C) were then exported as mesh geometries in ASCII file format. Further segmentation of the pulmonary trunk into anterior, right, and left segments based on the commissures between the pulmonary sinus cusps was performed manually using the Meshmixer software toolkit (Version 3.5.474; Autodesk, San Rafael, CA).

Automated distance measurements

The segmented mesh geometries were further analyzed using a custom-designed Python program (Version 3.6.3; Python Software Foundation, www.python.org) based on the state-of-the-art libraries for scientific computing *numpy* (Version 1.17.4) and *scikit*-learn (Version 0.20.3). After the mesh data for each segment and the coronary arteries were imported, each geometry was transformed into a cloud of 3-dimensional points. For each pulmonary trunk point, the minimal distance to the coronary arteries was computed by solving a mathematical minimization problem. To this end, an enumeration algorithm calculates the euclidean distances for all possible mesh grid points of the coronary arteries. A suite of automated tests was developed to ensure the correctness of the implementation.

Transformation into normalized 2-dimensional models

In order to project the mesh data for each patient onto a normalized 2-dimensional image, first the centerline of the pulmonary trunk was computed by means of regression lines between intersection points. Second, each of the pulmonary trunks was scanned vertically from top to bottom along this centerline with a fixed step size of 0.5 mm. At each step, the trunk was scanned horizontally for a total of 30 steps. The result was a 2-dimensional grid corresponding to points in the 3-dimensional geometry. At each point, the minimal distance to the coronary arteries was computed (see Automated distance measurements). The minimal distances were then visualized as a 2-dimensional image with normalized horizontal distance on the x-axis and the offset to the nadir of the corresponding pulmonary trunk determined on the y-axis (in millimeters). Images from all 3 segments were finally combined to give an impression of the entire situation.

Results

Fifty-eight patients (55% female; mean age 62 ± 2.0 years) were included in the analysis. Patient characteristics are

Table 1 Patient characteristics (N = 58)

Female gender (%)	55.2
Age (y)	61.6 ± 2.0
Body weight (kg)	81.3 ± 3.0
Height (cm)	169 ± 1.7
Body mass index (kg/m^2)	28.8 ± 1.2

Values are given as mean ± SD unless otherwise indicated.

summarized in Table 1. Mean minimal distance between the pulmonary trunk and the left coronaries was 1.4 ± 0.11 mm. On average, the closest relationship was located 13.8 ± 0.87 mm above pulmonary valve annulus. Figure 2 shows the distribution of the exact positions with the closest spatial relationship between the pulmonary trunk and the left coronaries. As illustrated, the heights of these positions vary widely and spread across the first 3 cm from the pulmonary annulus. For completeness, the distance between the pulmonary trunk and the proximal part of the right coronary artery as well as the distance between the left coronaries and the right outflow tract were further analyzed within a subset of patients. Mean minimal distance between the pulmonary trunk and the proximal right coronary artery was 16.34 ± 1.28 mm (n = 10). None of the patients exhibited a distance below 10 mm. Mean minimal distance between locations within the right outflow tract region just below the pulmonary annulus and the left coronaries was 6.3 ± 0.34 mm (n = 10); none of the patients exhibited a distance below 5 mm. Figure 3 shows the anatomic course of the left main and left anterior descending coronary arteries as well as the distance to the adjacent anatomic structures. As can be seen from the figure, the distance to the pulmonary trunk is significantly lower than the distance to the right outflow tract region below the pulmonary valve annulus.

Although the exact location of the minimal distance might be of potential interest, it has to be kept in mind that safety margins of several millimeters have been proposed to render coronary damage unlikely. Therefore, we next analyzed the anatomic distribution of different isodistances within the pulmonary trunk. Four typical examples of normalized 2-dimensional geometries showing isodistances <2 mm, 2–4 mm, 4–6 mm, 6–8 mm, 8–10 mm, and >10 mm are shown in Figure 4. Figure 5 illustrates the anatomic relationships between the pulmonary trunk and the proximal left coronaries of the examples shown in Figure 4 from below the semilunar valves in the parasternal cross-sectional view.

For systematic analysis, we subdivided the first 3 cm of the pulmonary trunk into 3 segments per cusp (0–1 cm, 1–2 cm, 2–3 cm) (Figure 6A: segments 1 to 9). The lowest segments of the left and anterior cusps (segments 8 and 9) were further subdivided vertically. The exact percentage of patients exhibiting a critical proximity based on a safety margin of 2, 4, 6, 8, and 10 mm per segment are listed in Table 2. Figure 6 shows the statistical distribution. We identified the anterior aspect of the lowest part of the LPSC (segment 8b) as well as the area between 1 and 2 cm above the nadir of the LPSC (segment 5) as the most critical regions. In >80% of patients, a safety margin of 4 mm could not be maintained within these 2 segments.

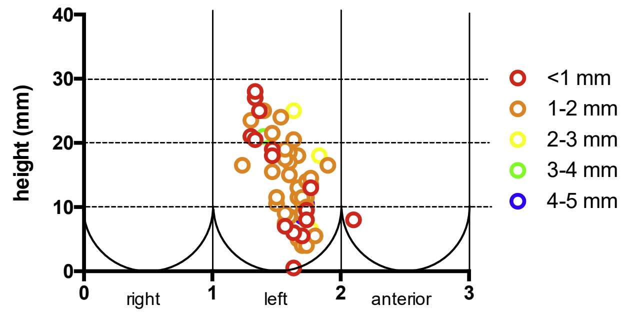

Figure 2 Location of closest spatial relationship. The exact location of the minimal distance between the pulmonary trunk and the left coronaries of all 58 patients are displayed on a normalized 2-dimensional geometry. The minimal distance to the coronaries is color-coded.

Analyzing whether a close spatial relationship can be predicted by simple clinical parameters, we next performed linear regression analysis between the minimal distance and biometric parameters, such as age, gender, body weight, height, and body mass index. We found that none of these clinical parameters correlated with the minimal distance (r^2 = 0.11, 0.027, 0.085, 0.0057, and 0.058, respectively). Similarly, there was no correlation between the height of the minimal distance and the clinical parameters (r^2 = 0.0001, 0.058, 0.002, 0.054, and 0.076, respectively).

Discussion

Main findings

Catheter ablation of RVOT-VAs from above the pulmonary valve using a reversed U-curve was introduced into clinical practice only a few years ago.[5–7] Although the close anatomic relationship between ablation sites within the pulmonary trunk and the coronary arteries has been reported, a systematic risk assessment has not been performed yet. To date, distance measurements have been performed manually

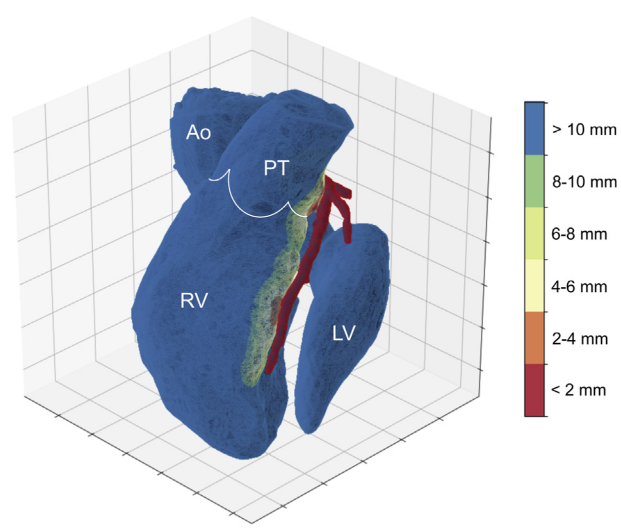

Figure 3 Proximity between the left main and left anterior descending coronary arteries and adjacent anatomic structures. Surface color illustrates the distance to the left coronary arteries. Ao = aorta; LV= left ventricle; PT = pulmonary trunk, RV = right ventricle.

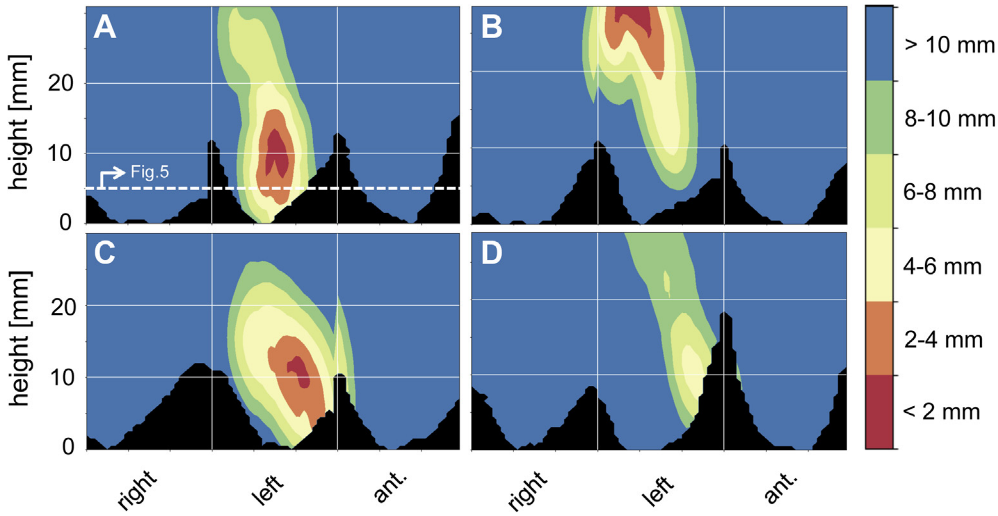

Figure 4 Exemplary isodistances projected on normalized 2-dimensional geometries. Although the closest relationship between the pulmonary trunk and the left coronaries is often located within the region of the left pulmonary sinus cusp **(A, C),** the coronaries also may pass higher **(B)** or without very close proximity **(D).** ant = anterior.

and are mainly limited to the distance between the LPSC and the left main coronary artery (LMCA).[9] However, manual measurements might not be adequate to address such a complex spatial relationship. Furthermore, sites of successful ablation are not limited to the LPSC. Using realistic anatomic reconstructions of the pulmonary trunk and the proximal left coronaries, we performed a comprehensive 3-dimensional analysis of the entire anatomic situation. This analysis was based on a newly developed algorithm that automatically determines the minimal distance between a given surface point of the pulmonary trunk and the proximal left coronaries. We confirmed that the proximal part of the left coronaries passes by the pulmonary trunk within only a few millimeters. We showed that the closest relationship is located at quite a variable height within the first 3 cm from the bottom of the LPSC. However, depending on the applied safety margin, the area at risk covers several segments of the pulmonary trunk and is not limited only to the LPSC.

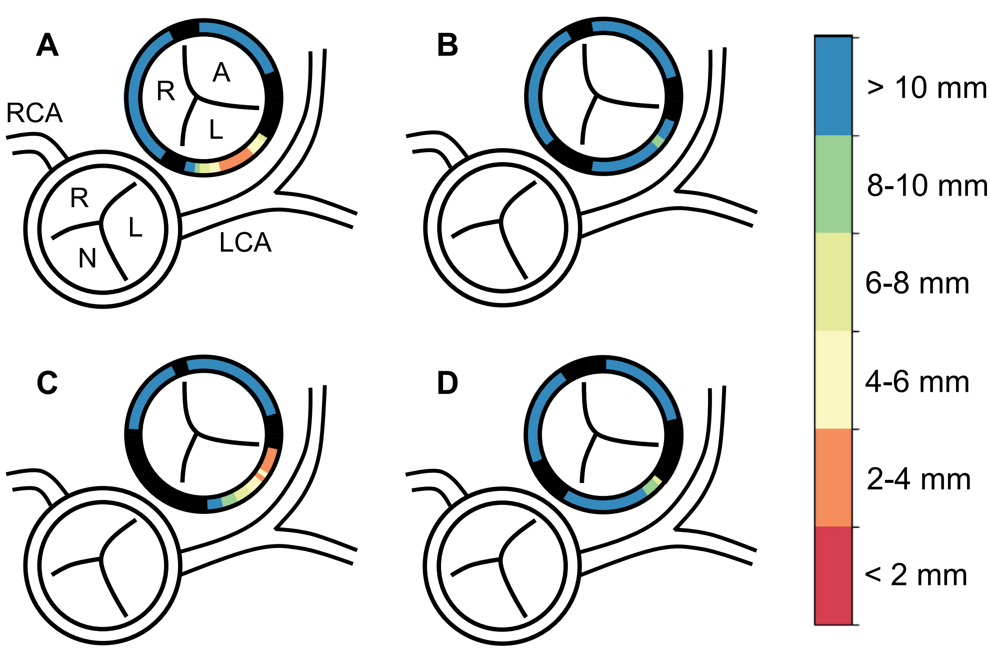

Figure 5 Spatial relationship in parasternal cross-sectional view. Distance values (see color scale) from the 4 examples given in Figure 4 at a height of 5 mm (*dashed line* in Figure 4A) are shown from a view below the semilunar valves. A = anterior cusp; L = left cusp; LCA = left coronary artery; N = noncoronary cusp; R = right cusp; RCA = right coronary artery.

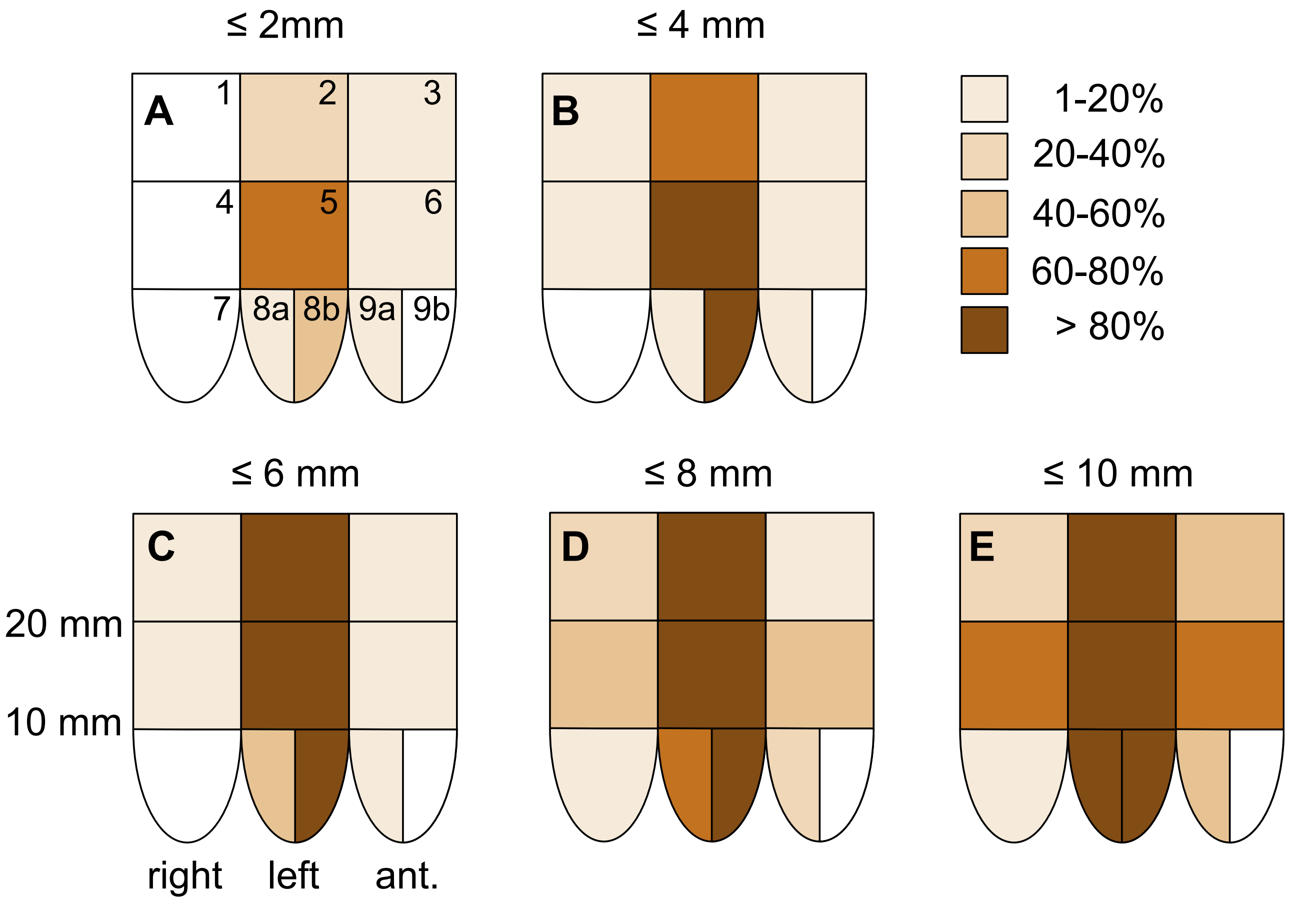

Figure 6 Statistical analysis of anatomic relationships within a certain threshold. The percentage of patients with proximity ≤2 mm **(A),** ≤4 mm **(B),** ≤6 mm **(C),** ≤8 mm **(D),** and ≤10 mm **(E)** is displayed per segment. ant = anterior.

Comparison with previously reported data

To date, only a few studies have addressed the anatomic relationship between potential ablation sites within the pulmonary trunk or the RVOT and the left coronary arteries. The studies available are based on data from coronary angiography, CT coronary angiography, intracardiac echocardiography, and inspection of anatomic specimens.[9,10,12] Recently, Dong et al[9] tested the hypothesis that a close anatomic relationship between ablation sites within the LPSC and LMCA can be predicted by the characteristics of the local cardiac electrogram. Using manual distance measurements within 2-dimensional planes as well as 3-dimensional reconstructions of CT scans, they analyzed the spatial relationship between the LMCA and LPSC. Depending on the individual anatomic situation, they found that 32%– 95% of patients exhibited a minimal distance below 5 mm within the LPSC.[9] These results are in line with our data (Table 2) showing 83% prevalence for a distance below 5 mm within the anterior half of the LPSC (segment 8b). However, direct comparison might be limited because the proximal part of the left anterior descending artery was not included in their analysis. Furthermore, within their study, distance measurements were restricted to a single pulmonary sinus cusp (LPSC). However, it is well recognized that ablation sites may be located within all 3 pulmonary sinus cusps and above.[9] Similar results were obtained by Walsh and Fahy,[10] who analyzed the anatomic relationship between the LMCA and adjacent anatomic structures. By manually determining the distances to the pulmonary artery within 100 CT scans, they showed a spatial relationship below 5 mm in 90% of patients. In contrast to our study, both publications were based on manual distance measurements and were limited to a small region of the pulmonary trunk.

Table 2 Percentage of patients with a minimal distance below a certain threshold within a pulmonary trunk segment

Segment	≤2 mm	≤4 mm	≤6 mm	≤8 mm	≤10 mm
1	0	3	12	29	40
2	34	62	84	93	95
3	2	2	5	19	45
4	0	3	14	28	60
5	79	97	100	100	100
6	3	5	19	45	74
7	0	0	0	3	10
8a	7	17	45	66	84
8b	57	83	100	100	100
9a	2	3	7	26	52
9b	0	0	0	0	0

Study limitations

First, the study population had a mean age of 62 years, and all CT scans had been performed in order to rule out coronary occlusion, lung embolism, and aortic dissection (triple rule-out). However, we realize that the population suffering from RVOT-VAs might be younger, so their anatomic situation could be slightly different. Second, both automated and manual segmentation have been performed using the interface between the contrast agent and the vascular surface; therefore, the indicated distances correlate well with the distance to the endothelium of the coronary artery. However, the distance to the vascular musculature might be underestimated.

Clinical implications

Accidental occlusion of coronary arteries has been reported as a rare complication of radiofrequency ablation within different anatomic regions of the heart.[11,13,14] In an experimental setting with a porcine animal model, epicardial radiofrequency ablation resulted in endothelial dysfunction as well as morphologic vascular damage when applied less than 5 mm away from the coronary artery.[15] Our data show that large areas of the pulmonary trunk are close to the proximal left coronaries. This information is of importance when delivering energy within the pulmonary trunk and should be borne in mind when adjusting power values or applying contact force. Furthermore, our data could help identify a subset of patients in whom possible complications should be anticipated or even ruled out by simultaneous coronary angiography. As indicated by our results, neither the minimal distance nor the position of the closest spatial relationship can be predicted by simple clinical parameters such as age, body weight, height, or body mass index.

Conclusion

By applying a newly developed mathematical algorithm for automated distance measurements within 3-dimensional geometries, we were able to systematically determine the distance between potential ablation sites within the first centimeters of the pulmonary trunk and the proximal coronaries. Our data add to the current understanding of the complex spatial relationship between both anatomic structures and might help to minimize accidental coronary damage during catheter ablation of RVOT-VAs from above the pulmonary valve.

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