Multislice computed tomography-based prediction of the implantation plane in transcatheter aortic valve implantation: determination of the line of perpendicularity and the implanter’s views

Andreas Holzamer, Emanuel Sitka, Christian Hengstenberg, Christof Schmid, Kurt Debl, Lars Maier, Daniele Cambonia, Oliver Hüscher, and Michael Hilker

Abstract

OBJECTIVES: We demonstrate a multislice computed tomography (MSCT)-based method to calculate the prediction of the so-called ‘line of perpendicularity’ (LOP) and the ‘implanter’s views’ (IVs) for transcatheter aortic valve implantation (TAVI) procedures. The LOP represents all possible angiographic angulations that result in an orthogonal view to the aortic annulus plane. The IVs allow visual confirmation of correct implantation planes, and are crucial for the commissural aligned implantation of second-generation TAVI prostheses.

METHODS: The LOP and IVs of 335 concomitant patients were prospectively analysed using multiple plane reconstruction (MPR) of the patient’s MSCT scans. Exclusion criteria were bicuspid valves (n = 18) and valve-in-valve TAVI (n = 15). In the MPRs, the aortic cusps’ lowest points were marked. With the marker’s three-dimensional coordinates, the graph of the LOP with the IVs was calculated and plotted using vector mathematics. In the last 244 cases, the IV with the right coronary cusp in front was chosen for the TAVI procedure. The finally used angulation was confirmed by aortic angiogram prior to the valve implantation. Solid angle differences that show the combined left anterior oblique/right anterior oblique and cranio/caudal movement of the C-arm allow quantification of corrections as well as demonstrate interindividual variations.

RESULTS: There is a broad interindividual variation of the aortic valve’s topology with solid angle variations of up to 74°. The shape of the LOPs is extremely varying, especially regarding the slope of the curve that indicates differences in valve orientations. Among the 244 patients for whom we used the prediction for the procedure, the first angiogram was considered perfect for implantation without further corrections in 97% (n = 237) of them. In case of the 7 patients with subsequent corrections, the mean solid angle between the prediction and the final angiogram prior to implantation was 6.2° (±5°); the largest correction was 14°.

CONCLUSIONS: Prediction of the implantation plane by analysing the patient’s MSCT is highly reliable in achieving an adequate view of the aortic annulus in TAVI. The analysis of LOPs showed the large interindividual differences that permit using a standard implantation plane. Therefore, we strongly recommend determining the LOP and IVs during the patient’s screening process in each single TAVI case.

Keywords: Transcatheter aortic valve implantation • Angulation • Line of perpendicularity • Implanter’s view

INTRODUCTION

Transcatheter aortic valve implantation (TAVI) has emerged as the treatment of choice for patients with symptomatic severe aortic stenosis who cannot undergo conventional aortic valve replacement [1, 2].

Since the first implantation in man in 2002 [3], considerable improvements in the preprocedural screening and sizing process have been made to achieve optimal procedural results. Especially the use of multislice computer tomography (MSCT) with the possibility of three-dimensional (3D) reconstruction of the complex anatomy of the aortic valve apparatus has become the cornerstone of procedural planning in TAVI [4–7].

As fluoroscopy remains the standard imaging modality during the TAVI procedure, the 3D anatomy derived by MSCT needs to

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be transferred to the angiographic suite. Apart from correct anatomical sizing for prosthesis selection, the prediction of the correct implantation plane using MSCT seems to be a promising feature. To avoid erroneous implantation of the TAVI prosthesis too high or too low within the aortic annulus, the precise choice of a C-arm angulation to fluoroscopically visualize the aortic annulus plane in an orthogonal view is essential.

The final implantation view needs to be confirmed by aortic root angiogram with injection of contrast media into the aortic root. In this aortogram, all three aortic cusps must be identifiable and aligned to ensure an orthogonal view to the aortic valve's annulus.

The 'line of perpendicularity' and 'implanter's views'

The angulation of the C-arm is commonly notated as cranio/caudal and left anterior oblique/right anterior oblique (LAO/RAO) angle deviation from the anterior–posterior position. Theoretically, a perpendicular view to the aortic valve's annulus can be achieved by an infinite number of angulations as the C-arm of the fluoroscope could rotate around the patient's aortic valve's plane. Therefore, for each patient an individual so-called 'line of perpendicularity' (LOP) that represents all possible angulations of the C-arm with an orthogonal view to the aortic valve can be constructed. This graph contains the three angulations that show one of the cusps just between the two others and are feasible for implantation. Possible 'implanter's views' (IVs) for the procedure are the one with the right coronary cusp (RCC) in the front and the middle of the acoronary (ACC) and left coronary cusp (LCC) in the chosen angulation. TAVI: transcatheter aortic valve implantation.

Figure 1: Fluoroscopic aortogram with contrast agent administered to confirm a proper implantation plane in TAVI. The view is orthogonal to the aortic annulus plane as all three cusps are aligned. The right coronary cusp (RCC) is in the front and in the middle of the acoronary (ACC) and left coronary cusp (LCC) in the chosen angulation. TAVI: transcatheter aortic valve implantation.

and Fig. 3 shows the corresponding line of perpendicularity with markers for the IVs (A–C). If only two cusps can be seen in the angiogram, the view could be from either a too caudal or cranial view, as the third cusp will be overlapped by one of the others. This is illustrated in Fig. 2D, where the depicted view is ~45° oblique to an orthogonal one.

We demonstrate a novel method to calculate the line of perpendicularity with the three IVs by MSCT scan using 3D coordinates of the aortic cusp's hinge points to facilitate the TAVI implantation.

METHODS

Patient population

We included 335 consecutive patients who underwent TAVI between February 2013 and August 2014 in our institution.
these, 18 patients with bicuspid valves and 15 patients with degenerated bioprostheses who underwent valve-in-valve TAVI were excluded. The indication for TAVI was discussed in the interdisciplinary Heart Team, and the implantation was performed in a hybrid operating theatre in cooperation with a senior cardiologist and cardiac surgeon. All patients gave their written informed consent to the procedure, MSCT acquisition and the University of Regensburg Medical Center’s TAVI Database.

Multislice computed tomography image acquisition

The MSCTs were performed with a 64-detector row computed tomography scanner (Siemens Somatom Definition Flash) using a dedicated TAVI protocol. A bolus of 60 ml of contrast media was administered at a flow of 15 ml/s via peripheral venous access. Data acquisition was performed gated to the electrocardiogram to allow retrospective gating and reconstruction of an end-systolic (70%) dataset.

Multislice computed tomography analysis

All MSCTs were analysed using multiple plane reconstruction (MPR) prior to TAVI. The MSCT data were analysed using the latest available version of the OsiriX software (Pixmeo, Geneve, Switzerland).

Definition and determination of the line of perpendicularity and implanter’s view

In the MPR mode, the lowest points of the aortic cusps (so-called ‘hinge points’) were identified and marked with the ‘point’ ROI-Tool of OsiriX. The positions of the points in the CT data volume are given as 3D coordinates for the x-, y- and z-axis (Fig. 4). The hinge points’ coordinates are the only required information to calculate both the LOP and the IVs in our method. Based on vector mathematics, we developed ready-to-use formula to calculate both the LOP and IVs. All results were converted to the previously described commonly used C-arm notation, with positive values indicating LAO or cranial and negative values RAO or caudal, respectively.

The LOP can be plotted using the formula shown in Fig. 5a, which gives the individual correlation of LAO/RAO and cranial/caudal differences of two angulations for quantitative assessment of the ‘real-world’ deviation between two different C-arm angulations. The used formula for the calculation of the LOP and the IVs were implemented in an Excel Sheet (Excel for Mac 2011, Microsoft, Redmont, USA) to automatically calculate and plot the LOP with the IVs as marker points after input of the nine coordinates (Fig. 6).

Implementation of the implantation plane during transcatheter aortic valve implantation

The MSCT-based formula to calculate the individual LOP and the IV with the RCC in the centre and front were applied for all 302 included patients. Initially, the calculations were made in addition to previously used methods of prediction like 3D volume rendering, orientation of the calcification of the native valve or semiautomated methods like the Heart Navigator by Philips or the 3MensioValves software. As the method seemed to be promising, we started to use the calculated C-arm angulation for the last 244 cases. An aortogram was performed and two senior TAVI operators who were personally not involved in the calculation of the predictions visually evaluated...
the appropriateness for implantation. If necessary, the angulation of the implantation plane was manually corrected using fluoroscopic guidance and repetitive aortograms until a suitable C-arm angulation for implantation was detected. The angulation of the C-arm in which the valve was finally implanted was documented and the deviation from the predicted C-arm position was calculated.

**Statistical analysis**

All data were prospectively collected and are depicted as the mean ± standard deviation or the median with the interquartile range as appropriate. The differences between the predicted implantation plane and the final implantation plane were calculated using the concept of solid angles. These angles combine LAO/RAO and cranial/caudal changes and therefore quantify ‘real-world’ movement of the C-arm. Figure 5d gives the underlying mathematical formula. Exemplary, Fig. 3 shows the solid angle difference between two angulations (A and D equivalent to Fig. 2). Solid angles were calculated to describe both the interindividual variation in the collective as well as to quantify differences between the first and last angiogram prior to implantation. Statistical analyses were performed with SPSS Ver. 22 (IBM, USA).

**RESULTS**

**Individual anatomical variation of the line of perpendicularity and implanter’s view**

The analysis of the CT anatomy shows a broad interindividual variation of the topology of the aortic valve as shown in Fig. 6. The resulting IVs with the RCC in the centre and front vary in a range of 68° (40° to 28°) in the LAO/RAO and 66° (31 to –35°) in the cranio-caudal axis (Fig. 7). The maximum combined angle variation between the IVs with the RCC in front of 2 patients was 74°. Presuming a 5° range of solid angle deviance as acceptable, the often suggested LAO10/Cranial10 standard plane represented only 8% of the patients. The shape of the lines of perpendicularity is consequently also quite varying, especially regarding the slope of the curve that indicates the tilt of the valve to the IV (Fig. 6).
C-arm position was 6.2° (±5°, max. 14°).

Regarding the 244 patients with the predicted angulation used for the first intraprocedural aortic angiogram, the predicted angulation was considered to be suitable for implantation in 237 cases (97.1%) with no manual correction and accurate alignment of the three coronary cusps with the RCC in the centre and front. In the remaining 7 cases (2.9%) manual correction was necessary in order to achieve a suitable implantation plane. The final implantation plane could be detected by one further aortogram in all 7 cases. The mean solid angle between the predicted and the orientation plane could be detected by one further aortogram in all 7 cases. The knowledge of the LOP representing all possible angulations has important implications for the TAVI procedure. First, the TAVI operator is able to quickly select other angulations in case of unusual anatomy rendering the IV unfeasible for implantation due to extreme C-arm angulations. Secondly, it is possible to quickly switch to a second angulation during the implantation process. This feature is especially important for the so-called ‘next generation’ valves, where the exact knowledge of the commissural orientation is crucial to achieve safe and controlled procedures. Moreover, in the case of valve-capturing systems like the Medtronic Engager or JenaValve, inadequate angulations are not only unfavourable but also potentially harmful, as the valve deployment needs to be exactly oriented to the native cusps. In case of optionally commissural aligned implantations as the Symetis TA system allows, the alignment can only be assured by the use of a precisely orientated IV.

Prediction of the implantation plane

Regarding the 244 patients with the predicted angulation used for the first intraprocedural aortic angiogram, the predicted angulation was considered to be suitable for implantation in 237 cases (97.1%) with no manual correction and accurate alignment of the three coronary cusps with the RCC in the centre and front. In the remaining 7 cases (2.9%) manual correction was necessary in order to achieve a suitable implantation plane. The final implantation plane could be detected by one further aortogram in all 7 cases. The mean solid angle between the predicted and the final C-arm position was 6.2° (±5°, max. 14°).

DISCUSSION

Multislice computed tomography in transcatheter aortic valve implantation

High-resolution MSCT has emerged as the gold standard modality for preprocedural imaging in TAVI, and its use is recommended since it has shown to increase the patient’s safety [8, 9]. Apart from prosthesis sizing, MSCT data can be used to predict the implantation plane prior to the procedure. Several commercially available solutions are available now that offer semiautomated analysis of the aortic annulus (Philips Heart Navigator, 3Mensio Valves). Suitable angulations can be manually obtained after the analysis by rotation of the rendered 3D volume in the axis of the predetermined implantation plane. However, these commercially available software solutions are costly, require dedicated workstations in some cases and the automated steps of the analysis may not always be accurate if artefacts limit the quality of the CT scan.

Line of perpendicularly, implanters view and commissural alignment

Precise determination of the aortic hinge points in the MPR of the MSCT scan is necessary to obtain 3D coordinates that are used for further calculation. As these points define the aortic annulus used for TAVI sizing, the exact determination of their position in the MSCT data is mandatory anyway and is the first step of the sizing process in all software solutions and approaches [10]. As the implantator is responsible for the patient’s safety, visual confirmation of suggested hinge point detection is therefore still mandatory in all listed semiautomated solutions. We describe a straightforward method to use the 3D coordinates of the aortic cusps to generate the LOP with the IVs for the individual patient. The knowledge of the LOP representing all possible angulations has important implications for the TAVI procedure. First, the TAVI operator is able to quickly select other angulations in case of unusual anatomy rendering the IV unfeasible for implantation due to extreme C-arm angulations. Secondly, it is possible to quickly switch to a second angulation during the implantation process. This feature is especially important for the so-called ‘next generation’ valves, where the exact knowledge of the commissural orientation is crucial to achieve safe and controlled procedures. Moreover, in the case of valve-capturing systems like the Medtronic Engager or JenaValve, inadequate angulations are not only unfavourable but also potentially harmful, as the valve deployment needs to be exactly oriented to the native cusps. In case of optionally commissural aligned implantations as the Symetis TA system allows, the alignment can only be assured by the use of a precisely orientated IV.

Prediction of the implantation plane: angiographic methods

As far as the determination of the ideal implantation plane is concerned, another common approach is to angiographically determine the C-arm orientation using repetitive aortic angiograms and orientation of aortic calcification on fluoroscopy. However, this elegant method has the drawback of increased use of contrast agent and potentially causes further exposure to radiation for both the patient and the interventional team.

Previously reported techniques to achieve suitable predictions by MSCT showed benefits regarding the reduction of needed contrast agent, procedural time and kidney injury [11, 12]. Limitations of these techniques are the need for manual measurement in MPR or 3D volume reconstructions and the need for dedicated software in some cases. The prediction is limited to one single angulation per work step, and therefore the construction of the LOP has only been demonstrated by repetitive single measurements so far and is therefore not feasible for the routine sizing process of all patients.

Impact of anatomical variations

Using our technique, we were able to show that aortic anatomy varies considerably between patients, a finding that has not been reported in a comparable cohort so far. In our patients, 92% of the patient-individual predicted angulations differed by more than 5° from the often recommended LAO10°/Cranial10° angulation.
Using an inadequate oblique view to the implantation plane, the aortic valve’s cusps will overlay each other as shown in Fig. 2D. In this case, the annulus cannot be identified precisely in the aortic angiogram, resulting in potentially too high or too low deployment of the prosthesis. Subsequently, complications such as sub- or supraskirtal paravalvular insufficiency, coronary occlusion, impairment of the anterior mitral leaflet or the embolization of the prostheses to the ascending aorta or the left ventricle may occur. Therefore, the use of standard angulations should be definitely discouraged.

Another finding in the present study was that the use of other IVs than the selected one (RCC in the front and centre) appears to be unfeasible in the vast majority of cases as extreme C-arm angulations are not possible in the sterile room (OR). In addition, the choice of the IV with the RCC in front should offer less scattered radiation, a lower patient’s radiation dose and better image quality in comparison with the other IVs as it is the closest to an antero-posterior projection (Fig. 8).

With correct prediction of a suitable implantation plane in 97% of the investigated cases, our present method appears to be a promising approach for further simplification of the TAVI process.

Feasibility of the method in everyday routine and adoption in other institutions

As mentioned before, the aortic valve’s hinge points define the aortic annulus plane as it is described for TAVI [10]. All procedure-relevant CT measurements refer to this definition; the accurate determination of the hinge points is therefore the key during the sizing process and has to be performed anyway. Consistently, all currently commercial available software for TAVI sizing known to the authors require manual assessment (3Mensio Valves, Siemens SyngoVia) or at least manual confirmation (Philips Heart navigator) of the hinge points.

For prediction of the LOP and IVs by using our method, the only required manual work is to transfer the nine coordinates of the hinge points given by Osirix to the described Excel sheet. The effort to calculate the LOP and IVs is accordingly ~2 min of extra time during the preoperative patient screening.

In contrast to the Osirix software, the previously mentioned solutions do not display the 3D coordinates of marker points and can therefore not be used for our method so far. The Osirix software works exclusively on Macintosh platforms (OS X, Apple) and is available in a free open-source version (FOSS license) for research purposes and in a commercial certified version for primary diagnosis.

If an Osirix-based CT screening is already established, there is no special training required for the adoption of our method in other institutions. As all comparable types of the software require handling of MPRs, the effort to get used to Osirix for TAVI sizing is also negligible for physicians who are used to CT TAVI sizing, in our opinion.

Nevertheless, we are currently developing a dedicated TAVI plugin for the Osirix software that integrates our method in a guided sizing workflow. We assume this will facilitate the TAVI sizing process with Osirix and will make our method widely available to other institutions.

Limitations

One major issue regarding the prediction of the fluoroscopic angulation by MSCT analysis is the possibility of different placement of the patient on the CT and OR table. Assuming a complete plane positioning of the patient’s thorax to be the gold standard, the grade of rotation of the patient towards the table plane can be measured easily in the CT scan. We decided not to add this correction to our prediction as oblique positioning of patients is caused by reproducible anatomical characteristics such as scoliosis in most of the seen cases. Therefore, the positioning of the patient during the CT will be similar to that of the implantation and the addition of corrective angles could lead to a wrong prediction. Retrospectively, we would not have corrected the CT prediction due to oblique placement in case of the seven patients with different final angiographic angulations to the predictions. As the angulations of all other patients have been predicted correctly, we cannot recommend using corrective measurements.

We did not compare cases with predicted angulations to a pure angiographic approach due to several reasons. First of all, different benefits have yet been demonstrated for MSCT-derived predictions [11], although the cohorts were smaller and the method of prediction was not the same. As the CT scan is anyway used due to prostheses sizing issues, no extra radiation or contrast agent is required for our method. As long as the prediction is confirmed with a final angiogram, we do not see any potential disadvantages for the patients by a CT prediction. In conclusion, we considered a randomized trial with a non-predicted collective not to be justified, especially as the approach follows strict logic and any individual prediction will certainly be more expedient than using a random approach.
Retrospective comparison to a former collector of our institution was not feasible as we used different techniques for CT-derived predictions by calcium analysis or semiautomated software solutions (Philips Heart Navigator, 3Mensio Valves) in the past. Furthermore, the potential endpoints such as amount of used contrast agent, radiation and procedural time would have been affected by advanced experience of the Heart Team in a retrospective setting.

Conclusion

Prediction of the implantation plane by analysing the patient’s MSCT in the described way is a highly reliable and easy method to achieve an adequate view of the aortic annulus in TAVI.

The analysis of LOPs showed a large interindividual difference that permits using a standard implantation plane. With the advent of second-generation prostheses with commissural aligned positioning, the choice of a proper implantation plane has become even more crucial. We assume that the method helps to decrease the use of contrast agent, radiation exposure and procedural time in TAVI implantations. As MSCT has developed to be the gold standard in TAVI implantations, and as the patients’ anatomy is as varying as demonstrated, we strongly recommend to determine the LOP and IVs during the patient screening process in each single TAVI case.

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REFERENCES


APPENDIX. CONFERENCE DISCUSSION

Dr J. Grau (New York, NY, USA): You present another method to calculate the line of perpendicularity and utilized this approach in 307 cases who underwent TAVI to study and investigate the differences between the aortic anatomy of patients and the potential of the presented method to further simplify the TAVI process.

The authors’ conclusion is that it is possible to effectively predict the C-arm angulation using the DICOM viewer and custom mathematical formula. The method of creating a C-arm angulation method improves upon the previous approach of aortic angiogram and fluoroscopy by limiting exposure to radiation for both the patient and interventional team. In addition, it does not require manual measurements or dedicated software unlike alternative techniques for creating suitable predictions by multiple-slice CT. Their results demonstrate that the aortic anatomy varies considerably, as he has shown, between patients, and their technique offers a promising method to create a suitable patient-specific plane of view.

First and foremost, I want to congratulate the authors on pursuing new means of simplifying the TAVI procedure. It is studies like this that will help us foster the use of percutaneous aortic valve procedures throughout a variety of hospital environments. I have three questions.

The formula is quite involved. Who in the TAVI or TAVR team actually calculates and determines the line of perpendicularity and the implanters view prior to the operation in your center?

Dr Holzamer: In fact, this is one of the surgeons or cardiologists. We don’t have collaboration with our radiologists for this.

Dr Grau: So one of the surgeons does that for you?

Dr Holzamer: Yes.

Dr Grau: How easy is your method to be readily integrated into the armamentarium and practice of a standard TAVR team? If you had to transfer this to another institution, how easy do you think that is going to be?

Dr Holzamer: Well, we have the CT scan and we assess it on our laptops. In order to simplify the implantation we have one sheet where we have all measurements on, and we also have this excellent plot in the OR that we can use during the implantation to change the angulations.

Dr Grau: Finally, you stated that you were able to show the aortic anatomy varies considerably between patients, actually among patients. Could you quantify the error you see in the standard angulation methodology that we have used routinely in the past when compared to your personalized line of perpendicularity and implantation view?

Dr Holzamer: If you take a look at the inter-individual variation, you will see that the maximum deviation was 74 degrees in two patients. Therefore, deviation from standard planes will be quite high.

Dr Grau: Based on the paper you sent me, you are applying this method in another institution, how easy do you think that is going to be?

Dr Holzamer: Yes, we will transfer it to another institution.
In the beginning, we used the technique described by Achenbach where you take a look at the calcification of the valve. In later patients, we used other software solutions where you have a graphical representation of the aortic annulus, like the Heart Navigator software from Philips or 3 Mensio Valves to predict angulations. So we couldn’t really compare them.

Dr Grau: But you think this is a significant improvement with radiation exposure and so on?

Dr Holzamer: This work has been done, and we decided not to try to get data about patients without a prediction, because in the end you will always be better if you have a prediction and start with it than just starting nowhere. I think there is no justification to do this, as you will need more radiation and contrast, and the effect has been shown for other methods, yet.

Dr T. Walther (Bad Nauheim, Germany): I just want to make a short comment on who is predicting the angulation. I have to say those interventionalists who implant those devices need to know how to look at the right angle, how to find the right angle, you need to know how to read the CTs and so on. Maybe a radiologist would not do other specific analyses, but you need to understand the data and need to look at the data prior to implantation, because it is your responsibility which valves you implant and at which angulation and so on.

I want to ask you, you mentioned the contrast several times. What is your average contrast load in these 244 patients?

Dr Holzamer: It depends, of course, on the choice of transapical or transfemoral approach. Transapical is about 50ml and transfemoral very varying, but I think, in means, 80-90 ml.

Dr V. Bapat (London, UK): I think this is a very good topic. OsiriX is free software, most of us use it, unless you have licensed software, which you must have used.

Dr Holzamer: Actually you can buy an FDA cleared version of OsiriX.

Dr Bapat: I think one of the questions was portability of this method to other centres. Most of us have OsiriX on our Mac. Do you think that there is a scope to be able to develop a plug-in? What I find difficult with OsiriX is your formula is a little too complex for me, but if you have a plug-in which is developed that once you do a 3D reconstruction you can get the views and then you can match it to the approach.

For example, for transapical maybe, if you are doing it, you want low but cranial because caudal is going to be difficult to operate. If you are doing transaortic, you want slightly different angles but the same plane. So do you think that you are going to develop a plug-in, which will allow the portability for all of us to use this supposed method?

Dr Holzamer: Actually we plan to do this, yes, because OsiriX gives you great opportunities as it is not dedicated or made for TAVI in special. In fact, if you check PubMed for TAVI and OsiriX you will find no matches. But this gives you great chances to do new things like measurements on other valves or structures you are interested in. But, of course, it is not as user friendly as special made software for TAVI. Therefore, the idea of doing a plug-in for the whole community to give somehow a workflow and to automate some steps is a good idea, and we thought about this.

Dr Bapat: I think that is the key. Most of us have it but we just don’t know how to translate those angles into reality.