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Feasibility of Fully Automated Motion Compensated Overlay for Transcatheter Aortic Valve Implantation

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Abstract

Background: Automated motion compensation of aortic root overlay on fluoroscopy during transcatheter aortic valve implantation (TAVI) could ensure accurate device positioning at minimal contrast cost, thereby reducing complication rates.
Objectives: To describe the feasibility of software that automatically compensates for cardiac and respiratory motion on X-ray, which may allow greater device control during TAVI.
Methods: Twenty four TAVI cases (25,607 frames) from four independent institutions using either the Medtronic CoreValve (n=8) or Edwards Sapien valve (n=16) were post-processed with the software. For each case, the algorithm applied three steps: (i) Generation of an anatomical roadmap using X-ray (Vascular Outlining, or VO) or 3D segmentation of CT data, (ii) Correlation to pigtail catheter, and (iii) Real-time motion compensation.
Results: VO motion compensation was activated 84% of all frames yielding a relative displacement error of -1.09 ± 2.65 mm. Similarly, CT-aided motion compensation was activated 84% of frames yielding a relative displacement error of -0.77 ± 2.92 mm.
Conclusions: We have shown feasibility of the first fully automated motion compensation method for real-time continuous visualization of the target aortic anatomy during TAVI procedures. Our method has the potential to improve valve positioning accuracy and reduction in deployment variability.

Key Words
Aortic stenosis • TAVI • TAVR • Imaging modalities • Non-invasive imaging

Introduction

With over 250,000 procedures conducted worldwide in the last decade, transcatheter aortic valve implantation (TAVI) has gained widespread acceptance for the treatment of aortic valve disease [1]. As outcomes continue to improve, TAVI is expected to be performed in younger, lower-risk patients [2] and will grow the number of procedures further. Correct positioning of the artificial valve is crucial for TAVI outcome [3]. Current implantation of prosthetic aortic valves

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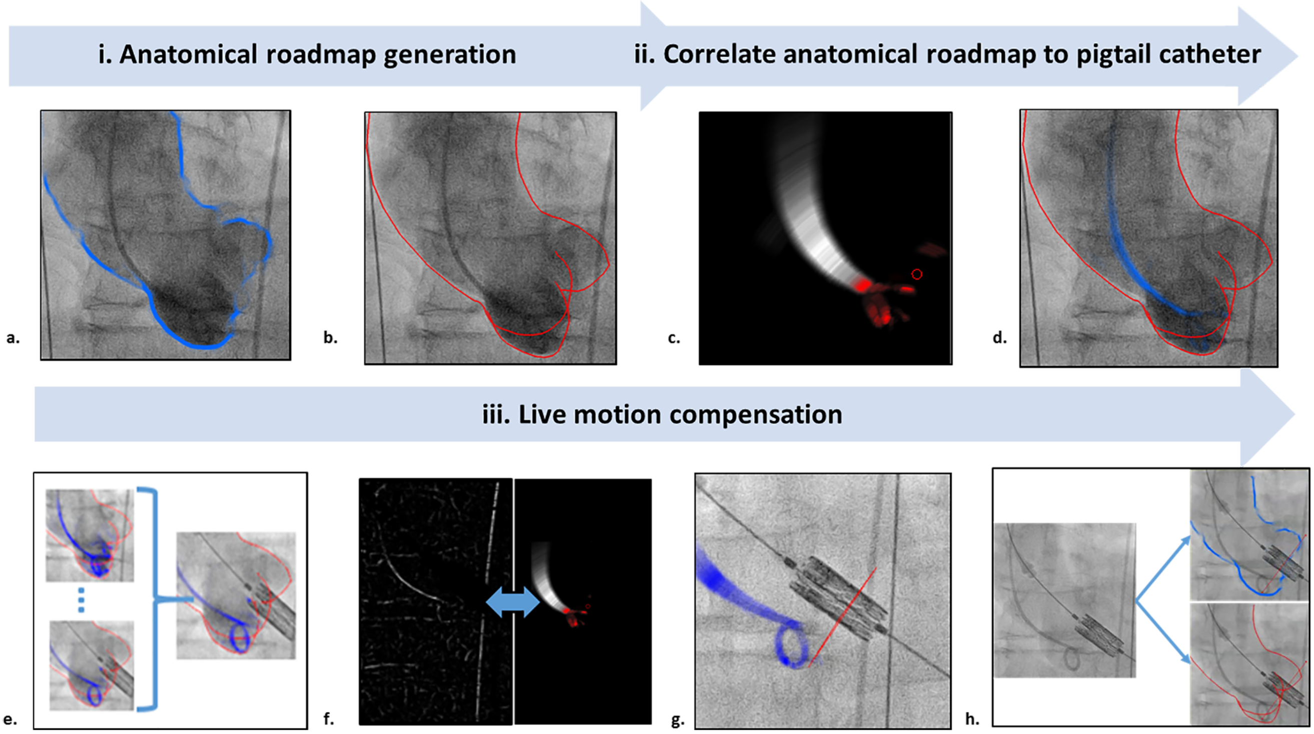

Figure 1. The three steps of motion compensation: i. Anatomical roadmap generation: *(Panel A)* Vascular Outlining (VO) based on the angiographic image, *(Panel B)* Computed-Tomography (CT) segmentation registered to the angiographic image. ii. Correlate anatomical roadmap to pigtail catheter: *(Panel C)* The reference map for the pigtail is extracted, *(Panel D)* The spatial relation between the pigtail reference map *(blue)* and the anatomical roadmap *(red)* is set. iii. Live motion compensation: *(Panel E)* The pigtail reference map best matching the current pigtail shape is selected, *(Panel F)* Live fluoroscopic image is filtered *(left)* and matched to the pigtail reference map *(right)*, *(Panel G)* Fluoroscopic view of the matching result, *(Panel H)* The transformation is applied to the anatomical roadmap resulting in a dynamic motion-compensated roadmap, either VO *(blue)* or CT *(red)*.

outside the optimal depth range still occurs in 21% of the cases [4], resulting in high-degree atrioventricular block (10-30%) and paravalvular leak (4-35%) [5]. We have created a fully-automated software that enables anatomical roadmap overlays on live fluoroscopic images compensated for cardiac and respiratory motion without workflow disruptions, which may allow for greater control over valve placement. This paper describes how our technology works and reports on the results of the feasibility study performed.

Method

Our algorithm comprises three steps:

i. **Anatomical roadmap generation.** Angiograms with contrast injections are automatically identified and the frame best opacifying the aortic root is selected by the algorithm, upon which two types of anatomical roadmaps are generated:
   1. Vascular Outlining (VO): The outline of contrast is detected in the X-ray image (Figure 1a).
   2. Computed Tomography (CT) aided: The automatic CT segmentation [6, 7] is registered to the angiographic image (Figure 1b).

ii. **Correlate anatomical roadmap to the pigtail catheter.** The pigtail catheter is routinely locked in an aortic valve cusp and its motion reflects overall aortic valve motion. The software searches for the pigtail catheter (Figure 1c) and sets the spatial relationship with respect to the anatomical roadmap (Figure 1d). This correlation process is performed for all angiograms producing a series of references (Figure 1e).

iii. **Live motion compensation.** Each live fluoroscopic image is filtered to enhance pigtail-like objects, which is then matched to the references (Figure

Table 1. VO and CT-aided motion compensation results.

			VO MC			CT-aided MC		
Valve type	**Pigtail catheter cusp position**	**Number of cases**	**Frames with activated MC (%)**	**Relative displacement error (mm)**	**Absolute displacement error (mm)**	**Frames with activated MC (%)**	**Relative displacement error (mm)**	**Absolute displacement error (mm)**
CoreValve	Lowest	8	82	-1.10±2.61	2.00	85	-1.13±2.91	2.15
Sapien	Lowest	4	87	0.09±2.56	1.97	98	-0.15±2.45	1.50
	Middle	12	89	-1.24±2.72	2.71	80	-0.09±3.02	2.48
Total	**-**	**24**	**84**	**-1.09±2.65**	**2.24**	**84**	**-0.77±2.92**	**2.22**

1f-g). The anatomical roadmap is then transformed accordingly to obtain a real-time dynamic motion-compensated roadmap (Figure 1h). Motion compensation is deactivated automatically if the pigtail catheter is obstructed, such as by the TEE probe, and activated when the pigtail catheter is successfully found again.

The live motion compensation is real-time up to 30 frames per second using an Intel® Xeon E5-1620 v3 CPU 3.50GHz.

Automatic Motion Compensation Evaluation Protocol

The use of a motion compensated overlay occurs during the device positioning and deployment phase, so we post-processed X-ray data of 24 cases during this phase to evaluate the algorithmic performance. None of these datasets were used for algorithm development.

First, the percentage of frames in which motion compensation was correctly activated by the algorithm was determined. Secondly, the relative and absolute displacement error were determined for every X-ray frame by comparing the manually annotated pigtail catheter and aortic root position with the algorithmic roadmap position, where a negative relative displacement error denotes deeper positioning by the algorithm. Continuous variables were given as mean ± standard deviation and categorical variables were given as percentages.

Results

For all 24 cases (25,607 frames) we evaluated the performance of motion compensation (Table 1). VO motion compensation was activated 84% of all frames yielding a relative displacement error of -1.09 ± 2.65mm and 2.24mm absolute displacement error. CT-aided motion compensation was activated 84% of all frames yielding a relative displacement -0.77 ± 2.92mm and 2.22mm absolute displacement error.

The relative and absolute displacement error increased for the larger and hence more obstructive CoreValve and also increased when the pigtail catheter was positioned in the more obstructive middle position (Table 1). Overall VO and CT-aided motion compensation demonstrated similar performance.

Discussion

We have used the pigtail catheter as a contrast-independent landmark for motion compensation during TAVI without any need for software interaction. To our knowledge, only one approach has successfully tracked the aortic valve plane by using the calcifications on the aortic valve as contrast-independent landmarks [8]. A clinical trial correlated this approach with a promising reduction in the incidence of conduction disorders [9]. The feasibility of the approach was limited by the need to manually annotate the calcifications after every repositioning of the C-arm. Additionally, not every patient may have sufficient visible calcifications [10]. All currently available CT fusion solutions provide static overlays only.

Of the two motion compensation methods evaluated: VO has the advantage of requiring only a well-contrasted aortic root angiogram representing the current aortic anatomical situation. CT-aided motion compensation provides a richer 3D view, with the ability to integrate pre-procedural planning in the live roadmap.

A major limitation of the study design was the post-processing of data. Actual clinical use of motion compensation is needed to determine the impact of the motion compensated anatomical roadmap on valve positioning. Another limitation of the technology is its dependence on the pigtail catheter maintaining its position locked in one of the aortic valve cusps. It is important not to lose this position as the device is advanced, as the relationship between the pigtail and the valve plane is assumed constant. Whereas this is common in clinical practice during valve positioning, the pigtail is typically pulled in the last phases of deployment, implying that the motion compensated overlay may not be used for guidance if any final adjustments are required. Further studies are warranted to examine whether these limitations are clinically acceptable. Of note, the live overlay is automatically disabled when detecting pigtail retrieval, to avoid erroneous guidance.

The implications of this work are perhaps greatest for enhancing the learning curve amongst new operators and for physicians performing TAVIs on lower-risk patients with potentially fewer X-ray-visible anatomic landmarks. Prospective studies of impact of this technology on contrast usage and positioning accuracy are warranted.

Conclusion

We have shown feasibility of the first fully automated motion compensation method for real-time continuous visualization of the target aortic anatomy during TAVI procedures. Our method has the potential to improve valve positioning accuracy and reduction in deployment variability and contrast usage.

Conflict of Interest

- Nick Assink – Master student located at Philips Healthcare)
- Maria-Louisa Izamis – Employee of Philips Healthcare
- Olivier Nempont – Employee of Philips Healthcare
- Marco Verstege – Employee of Philips Healthcare
- Cherif P. Sahyoun – Employee of Philips Healthcare
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- Navid Madershahian – In-kind support from Philips Healthcare
- Thorsten C. Wahlers – In-kind support from Philips Healthcare
- Peter G. Eshuis – Employee of Philips Healthcare

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