Percutaneous mechanical circulatory support in cardiogenic shock
Ouweneel, D.M.

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CHAPTER 4
ASSESSMENT OF CARDIAC DEVICE POSITION ON SUPINE CHEST RADIOGRAPH IN THE ICU: INTRODUCTION AND APPLICABILITY OF THE AORTIC VALVE LOCATION RATIO

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ABSTRACT

Objectives
The use of intracardiac assist devices is expanding, and correct position of these devices is required for optimal functioning. The aortic valve is an important landmark for positioning of those devices. It would be of great value if the device position could be easily monitored on plain supine chest radiograph in the ICU. We introduce a ratio-based tool for determination of the aortic valve location on plain supine chest radiograph images, which can be used to evaluate intracardiac device position.

Design
Retrospective observational study.

Setting
Large academic medical center.

Patients
Patients admitted to the ICU and supported by an intracardiac assist device.

Interventions
We developed a ratio to determine the aortic valve location on supine chest radiograph images. This ratio is used to assess the position of a cardiac assist device and is compared with echocardiographic findings.

Measurements and main results
Supine anterior-posterior chest radiographs of patients with an aortic valve prosthesis (n = 473) were analyzed to determine the location of the aortic valve. We calculated several ratios with the potential to determine the position of the aortic valve. The aortic valve location ratio, defined as the distance between the carina and the aortic valve, divided by the thoracic width, was found to be the best performing ratio. The aortic valve location ratio determines the location of the aortic valve caudal to the carina, at a distance of 0.25 ± 0.05 times the thoracic width for male patients and 0.28 ± 0.05 times the thoracic width for female patients. The aortic valve location ratio was validated using CT images of patients with angina pectoris without known valvular disease (n = 95). There was a good correlation between cardiac device position (Impella) assessed with the aortic valve location ratio and with echocardiography (n = 53).
Conclusions
The aortic valve location ratio enables accurate and reproducible localization of the aortic valve on supine chest radiograph. This tool is easily applicable and can be used for assessment of cardiac device position in patients on the ICU.
A growing number of patients are being treated with intracardiac assist devices and admitted to the ICU. Correct position of these devices is required for optimal function. Transthoracic echocardiographic (TTE) imaging is frequently used for assessment of device position but may be challenging as patients are frequently intubated and in the supine position. Often, these patients have poor acoustic windows that limit the diagnostic value of TTE, hampering appropriate echocardiographic assessment and decision making. Supine chest radiograph is done on a regular basis in patients admitted to the ICU. It would be of great value if intrathoracic device position could accurately be determined on plain supine chest radiograph. Specific cardiac structures, such as the native aortic valve, are difficult to localize on a supine chest radiograph image. We introduce a validated, easy, and reliable method to determine the aortic valve location (AVL) on standard supine chest radiograph by using anatomical landmarks to calculate ratios to determine the position of the aortic valve. Furthermore, we evaluated the accuracy of this method in patients admitted to the ICU for circulatory support (Impella, Abiomed, Danvers, MA) 1.

MATERIALS AND METHODS

The local institutional review board approved the study protocol. Several steps were taken to identify and evaluate the location of the aortic valve on supine chest radiograph, using both supine radiograph and CT images (Figure 1). First, potential anatomical landmarks were determined, that is, carina, thoracic width, lung apex, and diaphragm position. We measured distances between these landmarks and calculated ratios between these distances, which identify the position of the aortic valve (Figure 1). Several ratios with a possible relation to the AVL on chest radiograph were calculated and subsequently analyzed and are available in the Supplementary data. For the sake of conciseness, this article evaluates the novel AVL ratio, which was found to be the best performing ratio. The AVL ratio was determined by measuring the distance between the carina and the aortic valve divided by the thoracic width, measured at the inside of the thoracic wall, on the level of the medial section of the diaphragm at the level of the spine (Figure 1; and Supplementary Figure 1).

\[
\text{Aortic Valve Location Ratio} = \frac{\text{Carina - aortic valve}}{\text{thoracic width}}
\]
CHAPTER 4

1. **Aim:** Measure AVL ratio on supine chest X-ray
   **Method:** Measure the distance between carina and aortic valve prosthesis and thoracic width on supine chest X-ray (n=473)
   **Conclusion:** The AVL ratio defines the location of the aortic valve at a cranio-caudal distance of 0.28±0.05 (women) or 0.25±0.05 (man) times the thoracic width caudal to the carina (e-table 1)

2. **Aim:** Investigate if the AVL ratio is different in patients with and without aortic valve disease
   **Method:** Compare the AVL ratio, measured on CT, between TAVI (n=105) and angina pectoris patients (n=98)
   **Conclusion:** There is no difference in AVL ratio in patients with and without aortic valve disease (Table 1)

3. **Aim:** Compare the AVL ratio measured on CT with supine chest X-ray
   **Method:** Compare the AVL ratio measured on CT during screening with the AVL measured on supine chest X-ray after TAVI placement (n=105)
   **Conclusion:** The AVL ratio is different when measured on CT and supine chest X-ray. This might be due to differences in patient positioning for the two image modalities (e-Table 3)

4. **Aim:** Investigate the influence of mechanical ventilation, sternotomy and lung disease on the AVL ratio
   **Method:** Compare the AVL ratio measured on supine chest X-ray of patients with radiopaque aortic valve prosthesis
   **Conclusion:** There is no difference in AVL ratio when patients are mechanically ventilated, had a previous sternotomy or have lung disease (Table 2)

5. **Aim:** Investigate inter-observer agreement for thoracic width measurement
   **Method:** Compare measurements on supine chest X-ray of 2 independent observers
   **Conclusion:** There is a good intra-class correlation for thoracic width

6. **Aim:** Apply the AVL ratio, 0.28±0.05 for women and 0.25±0.05 for man, on patients on Impella support in the ICU
   **Method:** Locate the aortic valve on supine chest X-ray and compare the Impella position on X-ray with echocardiography findings (n=50)
   **Conclusion:** There is a good correlation between echocardiography and the AVL ratio to evaluate the position of the Impella (Figure 3)

Figure 1 Flowchart of the steps taken to calculate, evaluate, and apply the aortic valve location (AVL) ratio. Chest x-ray = chest radiograph; TAVI = transcatheter aortic valve implantation.

Because the native aortic valve is not visible on chest radiograph, supine chest radiographs of patients with an implanted radiopaque aortic valve prosthesis were analyzed (n = 473) (step 1). Then, the AVL ratio was validated using CT images of patients with angina pectoris without aortic valve disease (n = 98) and patients referred for transaortic valve implantation (n = 105) (steps 2 and 3; Figure 1). The influence of covariables on the AVL ratio was evaluated (step 4), and the interobserver variability was determined (step 5). Last, the AVL ratio was used to evaluate the position of an intracardiac assist device (Impella) in ICU patients. The position of the Impella on supine chest radiograph was compared with the corresponding TTE findings (n = 53) (step 6; Figure 1).
**Determination of the AVL Ratio**

Chest radiographs of patients who had received an aortic valve prosthesis either by surgical or transcatheter approach were analyzed (Figure 2). Supine chest radiographs of patients after surgical aortic valve replacement (SAVR) were obtained from 294 patients who were operated on between January 2013 and August 2014. Patients were excluded if the aortic valve prosthesis was not visible on radiograph \( n = 54 \), if it was not possible to evaluate the radiograph because of poor quality \( n = 4 \), or if the aortic valve prosthesis was not situated in the appropriate position because of anatomic abnormalities \( n = 1 \). Supine chest radiographs of patients after transcatheter aortic valve implantation (TAVI) were obtained from patients who had received an Edwards Sapien prosthesis (Edwards Lifesciences, Irvine, CA) between October 2007 and December 2014 \( n = 477 \). Patients were excluded if a supine chest radiograph was not available \( n = 232 \) or if the chest radiograph did not allow proper assessment of the AVL \( n = 5 \) or if the patient had previously undergone pneumonectomy \( n = 2 \).

Combining SAVR \( n = 235 \) and TAVI \( n = 238 \) patients resulted in 473 patients; the supine chest radiograph images of those were analyzed, and the AVL ratio was calculated. A total of 401 radiograph images were taken on the same day as the surgical (or TAVI) procedure, 27 were taken on day 1, and 22 on day 2 after the procedure, meaning that 95% of all radiographs were taken within 2 days of the procedure. The remaining 5% were taken within 3 weeks after the procedure.

**Validation**

In order to validate the AVL ratio, CT scans of consecutive patients without known valvular disease \( n = 98 \), referred for coronary artery calcium scoring, were compared with CT scans carried out during TAVI workup. In addition, CT scans carried out during TAVI workup were analyzed and compared with chest radiograph measurements of the same patient \( n = 105 \). The influence of a sternotomy, intubation, and lung disease (defined as FEV1/FVC ratio [FEV1%] < 75%) on the AVL ratio was assessed using chest radiographs. To evaluate interobserver variability, two observers independently measured the AVL ratio on supine chest radiograph of 122 TAVI patients.

**Monitoring Intracardiac Assist Device Position**

Supine chest radiographs were subsequently used to assess intracardiac device position (Impella) in ICU patients treated between January 2013 and November 2015 in our institution. The Impella (Abiomed) is a catheter-based axial blood pump, inserted into the left ventricle via the femoral artery. Echocardiography is currently the standard technique used to assess the position of the Impella. TTE evaluation of the position was carried out using the parasternal long-axis three-chamber view, showing both the aortic valve and the inlet area (Figure 3). For optimal positioning of the Impella, the inlet area
477 patients received an Edwards Sapien TAVI between November 2007 and December 2014. 238 patients with AP chest X-ray were excluded due to:
- no AP chest X-ray (n=232)
- valve not visible on AP chest X-ray (n=5)
- previous pneumonectomy (n=2)

105 CT scans were selected.

294 patients underwent a surgical aortic valve replacement between January 2013 and August 2014. 59 patients were excluded due to:
- aortic valve prosthesis was not visible on chest X-ray (n=54)
- chest X-ray not interpretable due to poor quality (n=4)
- aortic valve prosthesis placed more distally in the aorta (n=1)

235 chest X-rays were analyzed.

98 patients visited the outpatient clinic with angina pectoris and a CT scan was made between June 2013 and October 2014. 239 patients were excluded due to:
- no AP chest X-ray (n=232)
- valve not visible on AP chest X-ray (n=5)
- previous pneumonectomy (n=2)

203 CT scans were analyzed for aortic valve location.

Figure 2 Flowchart of patient selection.
AP = anterior-posterior, chest x-ray = chest radiograph, TAVI = transcatheter aortic valve implantation.
should be about 3.5 cm below the aortic valve annulus and well away from papillary muscle and subannular structures. The outlet area should be well above the aortic valve. The distance between the aortic valve annulus and the inlet area was measured by a cardiologist experienced in echocardiographic assessment of Impella position. A five-point scale was developed to evaluate the position of the Impella on chest radiograph (Figure 3). The position of the Impella on supine chest radiograph was then graded by an interventional cardiologist and a cardiovascular radiologist. If no agreement could be reached, a third cardiologist assessed the grading. Concordance of Impella position on chest radiograph and echocardiographic imaging was evaluated if the radiograph and echocardiographic imaging were performed within a 3-hour time frame.

**Figure 3** Comparison of the Impella position between supine chest radiograph (chest x-ray) and echocardiography.

A) Schematic image of the method to estimate the aortic valve location (AVL-ratio times the thoracic width).

B) Aortic valve position score on supine chest radiograph. If the Impella is correctly positioned, the aortic valve is just proximal to the curvature.

C) Schematic image of a transthoracic echocardiogram of the Impella catheter in the correct position (parasternal long-axis view). The Impella is at the correct position when the inlet area is 3.5 cm below the aortic valve annulus, away from the papillary muscle.

D) Comparison of Impella position as determined by echocardiography compared with supine chest radiograph.
**Data Analysis**

The ratios are shown as mean ± sd. Differences between groups were evaluated using the independent samples t test and Levene test. A paired sample t test was used to compare CT and radiograph measurements in the same patients. Interobserver variability was assessed using the intraclass correlation coefficient and by using a Blant-Altman plot.

**RESULTS**

**Location of the Aortic Valve on Supine Chest radiograph**

Several ratios with a possible relation to the AVL on chest radiograph were analyzed and are available in the Supplementary data. The AVL ratio, measured on the supine chest radiographs of 473 patients with a radiopaque aortic valve prosthesis, was found to be the best performing ratio. Several confounders of the AVL ratio were assessed in univariate and multivariate models. The model correcting for gender performed the best in estimating the distance between carina and the aortic valve (Supplementary data). The AVL ratio was 0.25 ± 0.05 in male and 0.28 ± 0.05 in female patients, respectively (Figure 1; and Supplementary Table 1). The distance between the carina and the aortic valve was 8.0 ± 1.3 cm for men and 7.8 ± 1.2 for women, respectively. The thoracic width was 31.8 ± 2.3 cm for men and 27.8 ± 1.7 for women, respectively (not corrected for magnification of the chest radiograph). The mean magnification of the chest radiograph, which was variable because of the use of a mobile radiograph device, was calculated using the documented size of the aortic valve prosthesis for calibration. The mean magnification was 1.1 ± 0.1. The AVL ratio was normally distributed (Kolmogorov-Smirnov, p = 0.100).

**Validation**

When measured on CT, the AVL ratio did not differ significantly between patients with and without aortic valve disease (Table 1). The AVL ratio measured on CT was compared with the measurement on a chest radiograph of the same patient (n = 105). The distances measured on the supine chest radiograph were corrected for magnification using the size of the aortic valve prosthesis. When assessed on CT scan, the AVL ratio was different than when measured on supine chest radiograph (Supplementary Table 3). The AVL ratio, measured on supine chest radiograph, was similar in patients with and without mechanical ventilation, sternotomy, and lung disease (Table 2). The intraclass correlation coefficient for the thoracic width is 0.979 with a mean difference of 0.1 cm and an sd of 0.6 cm (Supplementary Figure 2).
Table 1  CT measurements comparing transcatheter aortic valve implantation patients with and without aortic valve disease.

<table>
<thead>
<tr>
<th></th>
<th>TAVI</th>
<th>Angina Pectoris</th>
</tr>
</thead>
</table>
|                      | all           | men | women | all | men | women | p *
| Distances measured on CT (cm) |               |     |       |     |     |       |     |
| A: Carina - aortic valve | 105 | 5.4 ± 1.4 | 46 | 5.3 ± 1.6 | 59 | 5.4 ± 1.3 | 97 | 5.3 ± 1.1 | 46 | 5.4 ± 1.1 | 51 | 5.2 ± 1.1 | 0.451 |
| B: Thoracic width     | 95 | 28.4 ± 2.3 | 36 | 30.3 ± 1.8 | 59 | 27.3 ± 1.7 | 94 | 29.0 ± 3.3 | 44 | 31.3 ± 2.8 | 50 | 27.0 ± 2.2 | 0.126 |
| Calculated ratios     |               |     |       |     |     |       |     |
| A/B (AVL ratio)       | 95 | 0.19 ± 0.05 | 36 | 0.17 ± 0.04 | 59 | 0.20 ± 0.05 | 94 | 0.18 ± 0.04 | 44 | 0.17 ± 0.03 | 50 | 0.19 ± 0.04 | 0.413 |

* measurements are not corrected for magnification; SD=standard deviation;
Table 2  The influence of intubation, sternotomy, and lung disease on the Aortic Valve Location Ratio.

<table>
<thead>
<tr>
<th></th>
<th>AVL ratio</th>
<th>n</th>
<th>mean ± p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intubation</strong></td>
<td>0.335</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yes</td>
<td>318</td>
<td>0.26 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>no</td>
<td>132</td>
<td>0.27 ± 0.05</td>
<td></td>
</tr>
<tr>
<td><strong>Sternotomy</strong></td>
<td>0.604</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yes</td>
<td>388</td>
<td>0.27 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>no</td>
<td>61</td>
<td>0.26 ± 0.05</td>
<td></td>
</tr>
<tr>
<td><strong>Lung disease</strong></td>
<td>0.146</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yes</td>
<td>112</td>
<td>0.27 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>no</td>
<td>291</td>
<td>0.27 ± 0.04</td>
<td></td>
</tr>
</tbody>
</table>

**Monitoring Intracardiac Assist Device Position**

The position of the Impella, determined by the AVL ratio on supine chest radiograph, was compared with the position of the Impella on corresponding echocardiography images (Figure 3). Echocardiographic assessment of Impella position was done in 42 patients in the ICU, resulting in a total of 73 echocardiographic measurements with corresponding supine chest radiograph measurements. Cases were excluded because of 1) non-diagnostic echocardiography image quality with consequently unmeasurable Impella depth (n = 4), 2) more than 3 hours between performing the TTE and the radiograph (n = 17), or 3) repositioning of the Impella between the TTE and the radiograph (n = 2). This resulted in a total of 50 modality comparisons in 28 patients. Figure 3 shows a good correlation between the echocardiographic measurements and the grading of Impella position on supine chest radiograph measurements. Some examples of supine chest radiograph and corresponding echocardiography images are shown in Supplementary Figure 3.

**DISCUSSION**

This study shows that the location of the native aortic valve can be accurately estimated on supine chest radiograph. With this knowledge, we introduced a novel tool, the AVL ratio, which can be used for evaluation of intracardiac assist device position in patients in the ICU. The use of a supine chest radiograph to evaluate the position of an intracardiac assist device is very useful as supine radiographs are easily and frequently carried out on an ICU, whereas the quality of echocardiography is often impaired. If malposition of a device is suspected on supine chest radiograph, additional echocardiography can be done to further assess and adjust the position of the device. Based on our analyses,
we decided to use the thoracic width and the carina as anatomical markers to locate the aortic valve. The AVL ratio determines the location of the aortic valve using the thoracic width to calculate the distance between the carina and the aortic valve. This ratio seemed to be constant in patients both with and without aortic valve disease, but it is also constant in patients with and without mechanical ventilation and previous sternotomy. The AVL ratio was determined on supine chest radiographs of patients with an aortic valve prosthesis because the native aortic valve is not visible on chest radiograph. This patient population differs from the average population of patients treated with an intracardiac assist device, obviously in having been treated for severe aortic valve disease, but also in age (patients with an aortic valve prosthesis are generally older than patients treated with an intracardiac assist device). To assess generalizability of the AVL ratio derived from the patient population with aortic valve prosthesis, the AVL ratio was validated on CT scans of patients with angina pectoris (comparable with the patient population treated with intracardiac assist devices in mean age [57 ± 10 vs 60 ± 9 yr, respectively]; \( p = 0.938 \)) and the absence of major structural heart disease. The AVL ratio did not differ significantly between the patient populations (\( p = 0.413 \); Supplementary data). For the sake of generalizability, also the influence of sternotomy (i.e., conventional aortic surgery with sternotomy vs TF-TAVI without sternotomy) and mechanical ventilation on the AVL ratio was assessed (Table 2). In summary, these analyses indicated good generalizability of the AVL ratio derived from the population of patients with an aortic valve prosthesis to the patient population treated with a cardiac assist device and no difference in AVL ratio in patients with and without aortic valve disease, with or without sternotomy, and finally with or without mechanical ventilation. The value of the AVL ratio is different when measured on radiograph or CT images. This discrepancy might be caused by differences in patient positioning during examination. Although patients are in the supine position during both CT and chest radiograph, the position of their arms is different, as the CT is done with the arms elevated above the head of the patient, whereas the arms are alongside the body during the radiograph on the ICU. As the CT was carried out before the procedure and the radiograph was taken after the procedure, the location of the aortic valve is measured using the native valve on the CT images while using the location of the prosthesis on the radiograph, which might be a slightly different location. During CT, patients are requested to take a deep breath, whereas chest radiograph is not always synchronized with respiration as the patients might still be unconscious or intubated. Although the AVL ratio locates the aortic valve horizontally, it should be kept in mind that the aortic valve has an oblique orientation, which means that the distance between the most cranial and caudal location of the aortic valve may be a few centimeters. Using the AVL ratio to locate the aortic valve on a coronal view does not yield an exact location but a narrow range of its location. We evaluated Impella position using supine chest radiograph and compared the findings with echo-
cardiographic images. Maintaining the correct position of the Impella is a key factor in managing these patients. Patients are usually supported for several days, and assessing the position of the Impella needs to be as easy as possible. We have shown a good correlation of device position assessed by either supine chest radiograph images, the AVL ratio, or echocardiography. The sensitivity and specificity are 100% and 45%, respectively, with malposition defined as grade 1, 2, 4 or 5 on chest radiograph (Figure 3) and as a distance of greater than 7.0 or less than 1.0 cm between aortic valve and Impella inlet on echocardiography. The 100% sensitivity indicates that if the chest radiograph suggests that the device is well positioned, assessment of device position with echocardiography will suggest the same (i.e., no false negatives). However, the lower specificity indicates that chest radiograph may suggest device malposition, whereas in truth, the device is properly positioned. Therefore, the AVL ratio can be used as a screening tool as it gives a good indication of when echocardiography should be performed. Although we found a good correlation, there might be a slight discrepancy between the exact position of the device determined with both methods. For example, as the Impella device is freely positioned in the ventricle, across the aortic valve, it is able to move along with the contractions and/or filling properties of the left ventricle. The Impella device therefore is not in one fixed position. However, as the distance between the inlet and the outlet of the Impella 2.5 catheter is 6.5 cm, and even longer in the Impella CP (7.8 cm) or Impella 5.0 (8.0 cm), the Impella is in correct position within a certain range around the aortic valve. Another cause of discrepant findings between supine chest radiograph and echocardiography is the difficulty in some cases to visualize both the distal part of the Impella and the aortic valve in a single three-chamber long-axis view, which could result in accidentally measuring the Impella pigtail (which is around 3.5 cm in length) instead of measuring the Impella cannula. A limitation of our study that should be addressed is a possible change in Impella device position in the time between the echocardiography and chest radiograph. We therefore limited the time period between imaging modalities to 3 hours. Nevertheless, the position of the Impella could have been altered by the movement of the patient, altered filling properties of the left ventricle, or altered performance level of the Impella. The advantage of echocardiography imaging for evaluation of the position of intracardiac assist devices is the possibility to assess the relative position of the anatomical structures adjacent to the device (i.e., the mitral valve apparatus), instead of only the aortic valve. Also, cardiac function can be evaluated, and as stated above, the position can be adjusted under direct echocardiographic guidance. However, echocardiographic imaging is not always readily available, is time consuming, is operator-dependent, and necessitates the availability of a dedicated echocardiographer. Therefore, we propose a strategy of screening of the position of the intracardiac assist devices with an easily available supine chest radiograph and in the case of a presumed dislocation, further echocardiographic imaging. Previously, a bedside method to moni-
tor the position of an intraaortic balloon pump was proposed by measuring distances between puncture site in the right femoral artery to the sternal angle via the umbilicus, illustrating the need for a bedside measure to monitor device positioning.\(^2\) Chest radiograph is easily available and frequently used for screening and diagnosis of many diseases. In cardiology, chest radiograph is commonly used to calculate the cardiothoracic ratio (CTR), which is the ratio between the transverse diameter of the heart and the transverse diameter of the thorax measured on posterior-anterior chest radiograph. This ratio was first proposed by Danzer in 1919 to screen military recruits for cardiac enlargement.\(^3\) The relationship between cardiac dimensions on plain chest radiograph and cardiac function or cardiac disease is still the subject of debate, as positive as well as negative correlations have been described.\(^4,5\) Nevertheless, CTR is routinely used for initial assessment of the heart and can subsequently be supplemented by echocardiographic assessment of the cardiac function, illustrating the applicability of a ratio based on an easily available imaging modality. In this study, we used the AVL ratio to evaluate the Impella position, but there are many other devices that could benefit from this method, such as HeartMate PHP (Percutaneous Heart Pump, Thoratec Corporation, Pleasanton, CA).\(^6\) Because the routine use of the intraaortic balloon pump showed no clinical benefit in patients with cardiogenic shock after myocardial infarction\(^7\), and the guidelines allow other mechanical support devices in these patients\(^8,9\), it is to be expected that new mechanical support devices and other types of intracardiac devices will enter the clinical field. For this reason, easy and bedside evaluation of proper device position will be crucial. Evaluation of the position of intracardiac assist devices is a key factor in the management of these critically ill patients to ensure appropriate operation of these devices. It is important that evaluation of the position is easy and can be frequently performed to optimize the treatment of these patients.

**CONCLUSIONS**

The AVL ratio is a novel method to locate the aortic valve on supine chest radiographs. This new method is highly applicable in current clinical practice to evaluate the position of intracardiac assist devices in patients in the ICU, enabling appropriate operation of these devices. The AVL ratio determines the position of the aortic valve at a caudal distance from the carina of 0.25 times the thoracic width in male patients and 0.28 times the thoracic width in female patients.
REFERENCES


SUPPLEMENTARY DATA

Supplementary Table 1  Measurements on AP chest X-rays of patients with a radiopaque aortic valve prosthesis.

<table>
<thead>
<tr>
<th>Distances measured (cm) *</th>
<th>all</th>
<th>man</th>
<th>women</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Carina - aortic valve</td>
<td>455</td>
<td>8.0 ± 1.2</td>
<td>239</td>
</tr>
<tr>
<td>B: Thoracic width</td>
<td>460</td>
<td>29.9 ± 2.8</td>
<td>239</td>
</tr>
<tr>
<td>C: Aortic valve - diaphragm</td>
<td>445</td>
<td>6.2 ± 1.7</td>
<td>233</td>
</tr>
<tr>
<td>D: Carina - diaphragm</td>
<td>432</td>
<td>14.3 ± 1.8</td>
<td>225</td>
</tr>
<tr>
<td>E: Lung apex - diaphragm</td>
<td>442</td>
<td>24.9 ± 2.5</td>
<td>230</td>
</tr>
</tbody>
</table>

Calculated ratios

A/B (AVL ratio) | 448 | 0.27 ± 0.05 | 232 | 0.25 ± 0.04 | 216 | 0.28 ± 0.05 | <0.001 |
A/D | 432 | 0.56 ± 0.09 | 225 | 0.56 ± 0.08 | 207 | 0.56 ± 0.09 | 0.762 |
A/E | 430 | 0.32 ± 0.05 | 223 | 0.32 ± 0.05 | 207 | 0.32 ± 0.05 | 0.130 |
C/A | 432 | 0.82 ± 0.30 | 225 | 0.82 ± 0.27 | 207 | 0.82 ± 0.32 | 0.968 |
C/B | 438 | 0.21 ± 0.06 | 226 | 0.20 ± 0.05 | 212 | 0.22 ± 0.06 | <0.001 |
C/D | 432 | 0.43 ± 0.09 | 225 | 0.43 ± 0.08 | 207 | 0.43 ± 0.09 | 0.764 |
C/E | 439 | 0.25 ± 0.05 | 229 | 0.25 ± 0.05 | 210 | 0.25 ± 0.06 | 0.613 |

* measurements are not corrected for magnification; SD=standard deviation; AP=anterior-posterior

Supplementary Table 2  CT measurements - comparing TAVI and AP patients.

<table>
<thead>
<tr>
<th>Distances measured on CT (cm)</th>
<th>TAVI</th>
<th>Angina Pectoris</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Carina - aortic valve</td>
<td>105</td>
<td>5.4 ± 1.4</td>
</tr>
<tr>
<td>B: Thoracic width</td>
<td>95</td>
<td>28.4 ± 2.3</td>
</tr>
<tr>
<td>C: Aortic valve - diaphragm</td>
<td>105</td>
<td>7.9 ± 1.5</td>
</tr>
<tr>
<td>D: Carina - diaphragm</td>
<td>105</td>
<td>13.2 ± 2.0</td>
</tr>
<tr>
<td>E: Lung apex - diaphragm</td>
<td>67</td>
<td>23.1 ± 2.4</td>
</tr>
</tbody>
</table>

Calculated ratios

A/B (AVL ratio) | 95 | 0.19 ± 0.05 | 94 | 0.18 ± 0.04 | 0.413 |
A/D | 105 | 0.42 ± 0.24 | 97 | 0.42 ± 0.07 | 0.998 |
A/E | 67 | 0.23 ± 0.07 | 52 | 0.25 ± 0.04 | 0.128 |
C/A | 105 | 1.58 ± 0.56 | 97 | 1.43 ± 0.41 | 0.028 |
C/B | 95 | 0.28 ± 0.06 | 94 | 0.25 ± 0.05 | 0.001 |
C/D | 105 | 0.61 ± 0.14 | 97 | 0.58 ± 0.07 | 0.070 |
C/E | 67 | 0.35 ± 0.06 | 52 | 0.34 ± 0.05 | 0.260 |

CT=Computed tomography; SD=standard deviation, TAVI=transcatheter aortic valve replacement;
### Supplementary Table 3  Difference between CT and AP chest X-ray measured of TAVI patients.

<table>
<thead>
<tr>
<th>Distances measured (cm)</th>
<th>CT</th>
<th>X-ray *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>mean ± SD</td>
</tr>
<tr>
<td>A: Carina - aortic valve</td>
<td>102</td>
<td>5.4 ± 1.5</td>
</tr>
<tr>
<td>B: Thoracic width</td>
<td>93</td>
<td>28.4 ± 2.3</td>
</tr>
<tr>
<td>C: Aortic valve - diaphragm</td>
<td>99</td>
<td>7.9 ± 1.5</td>
</tr>
<tr>
<td>D: Carina - diaphragm</td>
<td>98</td>
<td>13.2 ± 2.0</td>
</tr>
<tr>
<td>E: Lung apex - diaphragm</td>
<td>64</td>
<td>23.0 ± 2.4</td>
</tr>
</tbody>
</table>

#### Calculated ratios

| A/B (AVL ratio) | 94  | 0.19 ± 0.05 | 0.28 ± 0.05 | <0.001 |
| A/D             | 100 | 0.42 ± 0.25 | 0.56 ± 0.09 | <0.001 |
| A/E             | 65  | 0.23 ± 0.07 | 0.32 ± 0.06 | <0.001 |
| C/A             | 100 | 1.59 ± 0.56 | 0.83 ± 0.32 | <0.001 |
| C/B             | 93  | 0.28 ± 0.06 | 0.22 ± 0.06 | <0.001 |
| C/D             | 100 | 0.61 ± 0.14 | 0.44 ± 0.09 | <0.001 |
| C/E             | 65  | 0.35 ± 0.06 | 0.26 ± 0.06 | <0.001 |

* corrected for magnification by measuring the size of the aortic valve prosthesis. SD=standard deviation.

### Supplementary Table 4  Different multivariate models for the AVL ratio, with corrections for gender, BMI and age.

<table>
<thead>
<tr>
<th>Model</th>
<th>Correcting variables</th>
<th>AVL – ratio =</th>
<th>Carina-aortic valve difference (measured and estimated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>0.27</td>
<td>Mean difference ± SD (cm) = -0.15 ± 1.37</td>
</tr>
<tr>
<td>2</td>
<td>Gender</td>
<td>0.28 – 0.027 (if male)</td>
<td>Mean difference ± SD (cm) = -0.05 ± 1.31</td>
</tr>
<tr>
<td>3</td>
<td>Gender, age</td>
<td>0.24 - 0.024 (if male) + 0.001*age</td>
<td>Mean difference ± SD (cm) = 0.93 ± 1.34</td>
</tr>
<tr>
<td>4</td>
<td>Gender, BMI</td>
<td>0.35 - 0.028 (if male) - 0.002*BMI</td>
<td>Mean difference ± SD (cm) = 0.31 ± 1.27</td>
</tr>
<tr>
<td>5</td>
<td>Age, BMI</td>
<td>0.27 + 0.001<em>age - 0.002</em>BMI</td>
<td>Mean difference ± SD (cm) = 0.70 ± 1.35</td>
</tr>
<tr>
<td>6</td>
<td>Gender, Age, BMI</td>
<td>0.30 + 0.002<em>BMI + 0.001</em>age -0.026 (if male)</td>
<td>Mean difference ± SD (cm) = 1.18 ± 1.29</td>
</tr>
</tbody>
</table>

We tested different models with corrections for gender, BMI and age. The models were designed by using a multivariate model to estimate the AVL ratio. After estimating the AVL ratio, the AVL ratio was used to calculate the distance between the carina and the aortic valve (by multiplying it with the thorax width). This estimated distance was compared with the measured distance on the supine chest X-ray images of patients with an aortic valve prosthesis. The difference between the calculated and measured distance between the carina and the aortic valve was smallest when only correcting the AVL ratio for gender (see table). The model only correcting for gender performed the best (smallest mean difference in estimating the distance between carina and the aortic valve. Therefore we have chosen to correct the AVL ratio for gender only. We believe it is important for the ratio to be simple and easily applicable, encouraging correction for gender only and not for additional variables.
**Supplementary Figure 1** Measured ratios
Several distances were measured to define the location of the aortic valve in relation to anatomical landmarks seen on chest X-ray. The anatomical landmarks used to measure the ratios are: (1) the tracheal bifurcation (carina), (2) the medial portion of the diaphragm at the level of the spine, (3) the apex of the lung and (4) the middle of the aortic valve prosthesis. The AVL ratio is defined as A/B in which A is the distance between the carina and the aortic valve and B the internal thoracic width at the level of the medial portion of the diaphragm.

**Supplementary Figure 2** Bland-Altman plot thoracic width
Bland-Altman plot of the thoracic width measured by 2 independent observers on supine chest X-ray of TAVI patients. The solid line represents the mean difference of -0.09 cm. The dashed lines represent the 95% limits of agreement.
Supplementary Figure 3  Examples of Impella position on supine chest X-ray images and corresponding echocardiography
A) The Impella is too far into the aorta; B) The Impella is a little too far into the aorta; C) The Impella is in correct position; D) The Impella is a little too far into the ventricle; E) The Impella is too far into the ventricle.