Transesophageal multiplane imaging of the human pulmonary artery: a comparison of MRI and multiplane transesophageal two-dimensional echocardiography

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Abstract

Objective: To evaluate the anatomical relationship between the esophagus and pulmonary artery including assessment of the correct transesophageal Doppler insonation angle into the mid-pulmonary artery trunk. Methods: We evaluated the anatomical relationship between the esophagus and pulmonary artery (PA) from comparable magnetic resonance (MR) and transesophageal echocardiographic (TEE) multiple two-dimensional images obtained in 10 healthy, young volunteers. Results: The main PA could be visualized with both techniques in all 10 volunteers and provided highly identical images of good quality. A mean insonation angle of 35° range 26° ± 46° for a fictive esophageal Doppler beam into the main PA was disclosed. The PA trunk was short with a mean length of 23.4 mm range 17–30 mm. Conclusions: These anatomical data contradict the general assumption of alignment of the pulmonary artery and the transesophageal Doppler beam. Angle correction should be applied in the clinical setting using MTEE by rotation of the scanning plane to approximately 45°. Ignoring the insonation angle of approximately 35° may cause 20% underestimation of blood flow velocity and cardiac output in the PA. © 1997 Elsevier Science B.V.

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1. Introduction

Cardiac output (CO) can be measured by transesophageal echocardiography (TEE) as the product of the cross-sectional area of the pulmonary artery (PA) and the time integral of the blood flow velocity obtained by pulsed Doppler ultrasound [1,2]. Assessment of the insonation angle (ϕ) (i.e., the angle between the ultrasound beam and the flow direction) is important for correct velocity determination because of the cosine relation in the basic Doppler equation:

$$\Delta F = \frac{2 f_0 \times v \times \cos \phi}{c}$$

where \(\Delta F\) is the Doppler frequency shift, \(f_0\) is the transmitted frequency, \(v\) is the blood flow velocity and \(c\) the velocity of ultrasound in soft tissue (approximately 1540 m/s). It is impossible to determine the exact direction of blood flow from a two-dimensional (2D) image when the vessel is transected obliquely. This is exemplified in Fig. 1 where the long axis of a straight vessel is insonated at a

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45° angle. By keeping this angle fixed and simultaneously rotating the imaging plane around the sector’s center beam line the changes in vessel shape are seen. Because the actual direction of flow remains constant, any imaging plane transecting the vessel apart from its long axis causes the flow to be oriented through the image plane (Fig. 1).

An insonation angle of 0° (i.e., cos φ = 1) has been a convenient assumption in most studies of CO as estimated from transesophageal spectral Doppler measurements in the human main PA (MPA) [3–5]. However, based on classical anatomical textbooks this assumption is an obvious oversimplification because of the complex anatomy of the MPA running upward, backward and to the left [6].

Transthoracic echocardiography (TTE) often provides low-quality 2D images of the MPA [7–10]. TEE enhances the image quality but the MPA can only be imaged in about 75% of patients using monoplane TEE, mainly due to acoustic distortion from the bronchial system [4,5,11]. This problem may to some extent be overcome by using biplane [12,13] or multiplane TEE (MTEE) [14,15]. Since MRI yields high-quality 2D images in any plane, visualizing both the esophagus and the PA system [16–18], this method is favorable for anatomical studies.

The purpose of this study was to evaluate the Doppler insonation angle between the esophagus and the pulmonary trunk using the ability of MTEE to provide anatomical information on the pulmonary trunk with MRI as a reference.

2. Methods

2.1. Volunteers

Ten unsedated volunteers with a mean age of 25 years (range 23–27 years) underwent two-dimensional multiplane TEE immediately prior to MRI examination.

Glycopyrrolate (Robinul®) 0.2 mg was administered intravenously after 4 h of fasting. Local pharyngeal anesthetic (Xylocaine®) spray was given prior to the insertion of the MTEE probe. MRI and MTEE were performed with the volunteer placed in the supine position. The ECG was monitored continuously and arterial blood pressure was measured prior to the examination with a conventional inflatable brachial cuff.

The investigation was approved by the local ethical committee according to the Helsinki II declaration and written informed consent was obtained.

2.2. TEE imaging

A Vingmed CFM 750 color Doppler apparatus and a multiplane 5 MHz TEE probe were used (Vingmed, Horten, Norway). Probe insertion was performed with the volunteer in the left decubitus position. At least 5 min was allowed to obtain hemodynamic stability before data acquisition. Gain and depth (8–9 cm) were adjusted to visually optimize the image quality and the sector angle was 70°.
The investigation commenced with imaging in the standard transversal image plane (0°) (Fig. 2). By rotating the MTEE ultrasound crystal in increments of 45° (clockwise when seen from the esophagus) 4 image planes (0°, 45°, 90° and 135°) were achieved. These imaging planes were chosen to standardize the multiplane approach. TEE images were continuously recorded on a S-VHS videotape for off-line analysis. The tip of the transducer was kept in a constant position in each volunteer by retaining the transducer tip at a fixed distance from the incisors. A Macin-tosh computer and the EchoPAC program (Vingmed, Horten, Norway) was used for digital storing and processing of the videograbbred data.

2.3. Magnetic resonance imaging

MR-images were obtained by means of a 1.5 Tesla Philips Gyroscan HP 15 S System using a cardiac triggered multi-slice spin echo pulse sequence. The following settings were used: echo time 20 ms, slice thickness 4 mm, slice factor 1.1, acquisition time 100%, matrix size 256 × 256 and 4 signal averages. The repetition time (TR) was adjusted individually according to the heart rate and the settings were used: echo time 20 ms, slice thickness 4 mm, slice factor 1.1, acquisition time 100%, matrix size 256 × 256 and 4 signal averages. The repetition time (TR) was adjusted individually according to the heart rate and the 256 and 4 signal averages. The repetition time TR was chosen to standardize the multiplane approach. TEE im-

2.4. Data analysis

Data analysis comprised:

2.4.1. Determination of the angle of insonation from the esophagus into the MPA

Since the 45° image was the one obviously best in alignment with the long axis of the MPA, the correct insonation angle can best be determined from this image projection (see the schematic illustration in Fig. 1 for explanation). The angle between a conceivable TEE Doppler beam and a conceivable velocity vector in the center of the mid-MA was evaluated (Fig. 5). This was done on the MR and MTEE 45° images by two observers blinded to the results of each other and to the MR images which were analyzed initially:

The scanning locus (i.e., the position of the tip of the transducer in the esophagus) and the distance (i.e., the center of the fictive range gate) to the tentative measuring point were first determined:

1. Assessment of the scanning locus on the 2D-images: During MTEE of the MPA the ultrasound crystal was positioned immediately caudal to the left main bronchus. This position is easily recognized since air in the bronchial system, in particular the left main bronchus, causes sudden image distortion or image loss. For assessment of the scanning locus on the MR images this information was used. Thus, in MR images, the scanning locus was defined immediately caudal to the left main bronchus guided by the esophageal balloon for verification of the esophagus (see Fig. 3). On the MTEE images the scanning locus was defined at the top of the sector.

2. Assessment of the fictive range gate: Using the various MR and MTEE images the midpoint of the MPA was determined. With a pair of compasses, the arc (1) through this midpoint was drawn with the scanning locus as the center (1a, Fig. 5 A, B) and using identical radius in each individual.

These features (assessment of the scanning locus and assessment of the center of the fictive range gate) were defined by the first observer (1) and used by both observers in the subsequent measurements and analysis.

3. Assessment of insonation angle: Inner and outer vessel walls were drawn on hard copies by two independent observers who were blinded to the results of each
Fig. 3. The principle used in this study for obtaining multislice MR images through the MPA. (A) the non-angulated transversal (0°) MR image was first obtained. The subsequent images were achieved by rotating the imaging plane (clockwise when seen from the esophagus) around an angulation line going through the center of the MPA and the center of the esophagus balloon. This is indicated by (ANG) in image A (see also Fig. 2 for better understanding of the spatial orientation of imaging planes); (B) image plane rotated 45°; (C) image plane rotated 90°; (D) image plane rotated 135°. EB = esophageal balloon; AA = ascending aorta; MPA = main pulmonary artery; DTA = descending thoracic aorta; RPA = right pulmonary artery; LPA = left pulmonary artery; LMB = left main bronchus; P = pulmonary valve.

Camera Obscura

Observer I used a visual method to determine the insonation angle (see Fig. 5A):
- By means of a ruler half of the distance between the inner and outer vessel wall was marked in 3 different locations: one in the center of the MPA (4a) and two symmetrically around here (4b, 4c). These points defined a new arc (4) through the middle of the MPA.
- At the intercept between (1) and (4) the tangent (5) to the arc was visually defined. This tangent was assumed to represent the flow direction at the center of the MPA.
- A straight line (6) between the scanning locus and (4a) was assumed to depict the direction of the ultrasound beam. Thus, the angle between (5) and (6) was determined to represent the insonation angle. This angle was measured by a protractor.

Observer II used a geometric method (very time-consuming but reduces the subjectivity incurred in the method used by observer 1) (see Fig. 5B):
- The scanning locus (1a), the arc (1) and the inner (2) and outer (3) vessel wall were defined as described above.
- The perpendicular on the line between (4a) and (4b) was raised on the basis of the intercept points (4c) and (4d) and thus defined line (4) (i.e., the ultrasound beam direction).
- The intercept between (1) and (4) defined the center of the vessel (5a) at the fictive range gate level along (1). Using 5a as the center of a circle (5) with a radius chosen to cut the inner and outer wall of the MPA (2 and 3), intercepts (6a), (6b), (7a) and (7b) are given.
- The perpendicular on the line between (6a) and (6b) was raised from the two intercept points (6c) and (6d). These points (6c and 6d) defined the line (6) which could be considered perpendicular to the tangent to (2) at the intercept point.
- Similarly, line (7) was constructed on the basis of (7a), (7b), (7c) and (7d).
- (8a) and (8b) represented the intercepts between the circle (5) and lines (7) and (6). The perpendicular on
Fig. 4. MTEE images (A1–D1) and corresponding MR images (A2–D3) recorded in one volunteer. The images were synchronously recorded by ECG triggering. For optimal comparison the MR images are rotated similarly to the displayed MTEE plane and an artificial sector angle has been superimposed. Almost identical MR and MTEE images in all 4 scanning planes could be obtained. (A) transversal plane; (B) 45° rotation from the transversal plane (clockwise rotation seen from esophagus); (C) 90° and (D) 135° further rotation from the transversal plane (see Fig. 2). In A3 to D3 (same as A2 to D2), the main pulmonary artery vessel wall is indicated in white ink. It is obvious that the pulmonary artery is cut oblique in A3 and D3 with a more longitudinal transection in B3 and D3.

the line between (8a) and (8b) was raised on the basis of intercept points (8c) and (8d). This line (8) was perpendicular to the bisector between (6) and (7), thus representing the mean-tangent to the inner and outer wall of the MPA (2 and 3). Line (8) was considered to indicate the main direction of MPA and the flow in the center of the MPA. The angle between lines 4 and 8 was considered representative of the insonation angle and was measured by a protractor.

2.4.2. Evaluation of the length of the main MPA
On diastolic MR-45° images (displayed the MPA to the greatest extent) (Fig. 5) the posterior border (bifurcation) was defined by extrapolating a line (PL) from the anterior

Fig. 5. MR-45° images (same as Fig. 3B) illustrating the method for determination of the insonation angle (A and B). (A) the visual method used by observer I; (B) the geometric method used by observer II; (C) the method for evaluating the length of MPA. PA_L, = the length of the pulmonary artery; PL = posterior limit of MPA; AL = anterior limit of MPA; X = scanning locus. See Section 2 for further explanation.
vessel wall of the right PA into the MPA. The anterior limit of MPA (AL) was defined by a line immediately above the closed pulmonary valve. Using a ruler the midpoints of AL and PL were found and connected as PA_L (see Fig. 5C). In this study PA_L defined the length of MPA.

2.5. Statistics

Paired t-tests were used to compare the determined angles from observers I and II and for comparison of the angles on MR-45° versus MTEE-45° images. The agreement in angle determination from MR-45° and MTEE-45° images between the two observers was assessed by the method described by Bland and Altman [19]. According to this method the limits of agreement are given as mean ± 2 s.d. where the mean value is the average of the differences between data and is ideally zero but may be either positive (+) or negative (−). s.d. = the standard deviation [19]. Provided the differences are normally distributed 95% of the differences will lie between these limits. All statistical analyses were preceded by a probability plot to verify a normal distribution of the variables. A P-value of < 0.05 was considered statistically significant.

3. Results

The MPA could be visualized with both techniques in all of the 10 subjects and highly identical images of good quality were achieved in all 4 scanning planes (Fig. 4).

Measured angles and P-values are listed in Table 1.

Table 1 shows the measured angles in degrees for observer I and II. Imaging did not make any significant difference to the angles determined by each of the two observers on the MR-45° and MTEE-45° images (column A vs B, column C vs D, in Table 1) (P > 0.05). The limits of agreement using the method described by Bland and Altman were −0.67° ± 2.67° (mean ± 2 s.d.) for MRI-45° (column A vs B in Table 1) (Fig. 6A) and −1.8° ± 9.54° (mean ± 2 s.d.) for MTEE-45° (column C vs D in Table 1) (Fig. 6B). The mean insonation angle determined on the 45° images (average of column A, B, C and D in Table 1) was 35.0° (range 26°–46°) (Table 1).

Fig. 6. Difference in angle determination on MR-45° images (A) and MTEE 45° image (B) between the two observers plotted against the mean value.
The estimated mean length of the MPA was 23.4 mm (range 17–30 mm). In one volunteer (No. 2) the PA valve could not be identified on the MR-45° image and information about the PA valve was obtained from the sagittal image. The mean distance from the scanning locus to the center of the MPA (center of the fictive range gate) was 48 mm (range 37–55 mm).

The average mean arterial blood pressure measured 87 mmHg (range 68–97 mmHg; s.d. 7.2 mmHg). The average TEE examination time was 14 min (range 8–22 min) and the MR scanning time for each of the 4 projections was approximately 20 min. No complications occurred during the examinations.

4. Discussion

4.1. Angle determination

In most MPA transesophageal Doppler studies the insonation angle is assumed to be 0° [3–5]. In a study by Savino et al. [11] the angle was evaluated from the transversal plane alone and assessed to be in the range of 0–28°. In another study by Schlüter et al. [20] the insonation angle was postulated to be close to zero. Stümper et al. [21] stated that pulsed Doppler interrogation into the MPA in the longitudinal (90°) imaging plane (bi-plane view) was less rewarding than transverse imaging because the angle of incidence between the ultrasonic beam and flow of blood approaches 90°. Our understanding is that this is not the case since imaging in the longitudinal plane does not change the angle of Doppler insonation. Provided there is a stable transducer position, rotation of the 2D-image does not affect the insonation angle, but the vessel will be transected differently. This optical illusion is a common misinterpretation and may easily lead to wrong conclusions, see Fig. 1 and Fig. 4.

In the standard transverse plane, the ultrasound beam transects the MPA in an oblique fashion, and may give the impression that the beam is actually in alignment with the direction of flow (Fig. 4, A1–A2). This is clearly inaccurate (Fig. 4, A3). The best possible way of correcting for this type of error is to obtain an image where the ultrasound beam transects the long axis of the MPA most favorably (Fig. 4B). This study disclosed the 45° imaging plane to be the most favorable. The average angle of insonation disclosed in this way was very close to 35° (Table 1). This assumes that the blood velocity vector is oriented parallel to the vessel wall and has recently been supported by an MR study using velocity vector analysis [22]. The fact that the same results have been obtained by the two different imaging and analysis techniques strengthens the validity of the estimated 35° insonation angle. Furthermore, the small difference in angle determination obtained on the MR 45° and MTEE 45° indicates, that the angle between the long axis of the MPA and a beam oriented from the esophagus towards the center of the MPA (i.e., the insonation angle) can be determined with an acceptable accuracy in a 45° MTEE image (Table 1). Based on our anatomical data the velocity may be underestimated by approximately 20% solely due to inappropriate assessment of the insonation angle. Our data also document that it is not feasible to provide a reasonable estimate of the insonation angle from the standard transversal plane alone but requires rotation of the imaging plane to approximately 45° until the appearance of alignment of the longitudinal axis of the MPA to the imaging plane.

4.2. Main PA length

The MPA length, as determined in this study, measured only 2–3 cm. This should be accounted for when measuring blood velocities in the MPA by means of Doppler ultrasound techniques because only subtle movements will easily cause extra-MPA sampling. Rotation of the scanning plane to approximately 45° during MTEE will minimize the risk of undesirable malpositioning of the sample volume towards the pulmonary valve or bifurcation where more complicated flow fields can be expected [16,22,23]. Furthermore, in this rotation plane Doppler sampling in the vicinity of the minor curvature can be avoided. Guidance of the Doppler SV is important (e.g., for CO purposes) because of the skewed cross-sectional velocity distribution, which has been proven earlier [24]. The magnitude of error due to this skewness in CO determination has recently been evaluated also in young healthy volunteers [25].

4.3. Limitations and future perspectives

In this anatomical study several measures were made to optimize the comparison between the MR and MTEE images. The main reason for choosing diastolic images was to achieve optimal time-correlated images. This was not possible during systole because of the relatively low MRI sampling frequency. We believe that the error incurred in translating from diastolic to systolic images is negligible. In addition, it should be emphasized that in the clinical setting during MTEE it is possible to perform individual angle correction from a systolic frame.

To obtain optimum image quality, the tip of the MTEE probe was often gently pressed against the esophageal wall by mild anteflexion. Thus, the exact spatial orientation of the ultrasound crystal and image plane could not be completely controlled. The good agreement of the results with MRI suggested that lack of complete spatial orientation of the MTEE imaging plane was a minor problem.

Data on anatomical changes caused by age or pathological conditions (e.g., chronic obstructive lung diseases, congenital and acquired cardiac diseases) should be gathered to reinforce the basis of reliable transesophageal Doppler velocity measurements in the human pulmonary artery. Errors due to a skewed velocity profile and difficulties in
assessment of the cross-sectional area of the vessel may further contribute to an unacceptable error in CO determination and certainly need to be addressed.

4.4. Conclusion

Our data showed that the assumption of a 0° insonation angle for transesophageal Doppler imaging into the MPA is a significant oversimplification. The ultrasound scanning plane should be rotated approximately 45°, allowing individual correction of the insonation angle. Ignoring the insonation angle of approximately 35° may cause 20% underestimation of blood flow velocity and cardiac output in the pulmonary artery by means of TEE.

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