Three-dimensional echocardiography for left ventricular quantification in heart failure

van der Heide, J.A.

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Importance of transducer displacement and tilting on three-dimensional echocardiographic volume assessment using apical or off-axis rotational acquisition: an in vitro study.

H.F.J. Mannaerts, O. Kamp, J.A. van der Heide, G. Valocik, C.A. Visser.

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Abstract

Objectives: The goal of this study was to assess effects of translation (horizontal displacement) and angulation (transducer tilting) on three-dimensional (3D) echocardiographic volumes of both balloons and human left ventricles after autopsy.

Methods: Six water-filled (non-) aneurysmatic balloons of 150, 250, and 350 ml and 3 hearts of different sizes and shapes were suspended upright in a water bath. Angulation and/or translation was performed respectively by tilting the transducer with a mechanical arm in a vertical plane relative to the balloon tip or true apex of the hearts and by shifting the water bath in the same vertical plane. For balloon and left ventricular (LV) volume assessment, a 3D conical data set was obtained by TomTec rotational acquisition in combination with a HP Sonos 5500 ultrasound machine.

Results: For the 6 balloons, translation from 1 to 4 cm yielded volumes of up to 74% of the optimal volume (100%); angulation of 10 degrees or 20 degrees, volumes of up to 80% and 34%. Translation with 10-degree angulation yielded volumes up to 64%; for 20-degree angulation and translation, there was no volume loss. Results were similar for the left ventricles.

Conclusions: Even minor angulation or translation of the transducer yields substantial underestimation of the true volume. Off-axis para-apical views, however, defined as angulation of 20 degrees and greater than 0.5 cm translation in this in vitro model, obviate volume underestimation. Such views in patients, if obtainable, may be an attractive alternative for conventional apical 3D acquisition, especially in dilated and aneurysmatic hearts.

Introduction

Accurate quantification of left ventricular (LV) volume and function is important in clinical cardiology because it has diagnostic, prognostic, and therapeutic implications [1-3]. Geometric assumptions and image-plane positioning errors, inherent to transthoracic 2-dimensional echocardiographic methods (2DE) for volume measurements, have largely been overcome recently by transthoracic three-dimensional echocardiography (3DE). Many recent studies have documented that 3DE, compared with previously established conventional methods, is highly accurate for volume and ejection fraction computation [4-8]. Several limitations, however, are applicable to both apical 2DE and 3DE: interference by interposed ribs, lung, or fat tissue, which limits the number of available acoustic windows and often obscures the true anatomical apex. Hence, the "echocardiographic apex" is often superior and anterior to the anatomic one, resulting in foreshortening [9]. Especially in 2DE, foreshortening may be an important reason for LV volume underestimation if an apical window were to be used for volumetry by single- or biplane Simpson's rule. Also in 3DE with the use of rotational acquisition through an apical window foreshortening will result in LV volume underestimation if the true apex and other parts of the LV are not entirely encompassed within the conical data set. A common limitation to both 2DE and 3DE may be partial cut-off of a dilated (aneurysmatic) LV due to the relatively limited 2D-sector angle, and in case of 3DE, limited top angle of 90 degrees of the conical data set.

The purpose of this study was to ascertain the absolute accuracy of 3DE by rotational acquisition and to simulate partial cut-off and foreshortening with the resulting volume underestimation. This was achieved in an in vitro model by using water-filled latex balloons, as well as autopsy specimens of a normal-sized heart, and a regionally and globally dilated LV. The above-mentioned conditions were simulated by creating various degrees of translation (controlled horizontal displacement of the transducer relative to the balloon tip or apex) and angulation (transducer tilting relative to the long-axis of the balloon or LV (0 degree), or the combination of these.

Methods

Balloon phantoms

We performed 2 types of experiments. Figures 1 and 2 show the experimental set up of our study. The balloons were immersed into a water bath, with the "apex" upward supported by suture strings attached to the water bath and linked with a 3-way stopcock by which the balloon could be filled accurately with a known water volume outside the water bath. After filling, care was taken to release air through the stopcock. First, to test the accuracy of the average rotation method10 for volumetry, a latex balloon was filled with water to 20 varying sizes (mean 225,5 ml, SD 109 ml, range 45-420 ml). These balloons were symmetrically distorted (dumbbell shaped) by sutures and adhesive tape. Also, "apical aneurysms" could be created in a similar fashion. In the second part of the experiment, the effect of translation and/or angulation of the transducer on the measured volumes was assessed by using 3 aneurysmatic and 3 nonaneurysmatic shaped balloons of 150, 250, and 350 ml.

Autopsy hearts

Three autopsy specimens, of which 2 were formalin fixed, were studied in a similar fashion as described previously, including a normal-sized LV (true water volume 44 ml), one globally dilated LV (121 ml), and one regionally dilated LV with an inferobasal aneurysm (46 ml) (figure 3). LV volumes were measured by filling the cavity with water through the mitral valve up to the level of the mitral annulus (true water volume); there was no leakage through the aortic valve in any of the hearts. Subsequently, the specimens were immersed into the water bath with the apex fixed in an upward position by using suture strings. Thus, the orientation of both the balloon and the LV within the water bath was similar. The water-filled (non) aneurysmatic latex balloons and the 3 autopsy hearts were suspended upright in a water bath with the balloon tip or apex 0,9 to 1,5 cm under the water surface mimicking the clinical in vivo condition of the apical acoustic window. In this position the hearts were vented from air through the apex with a large bore needle. The result was controlled by echocardiography.

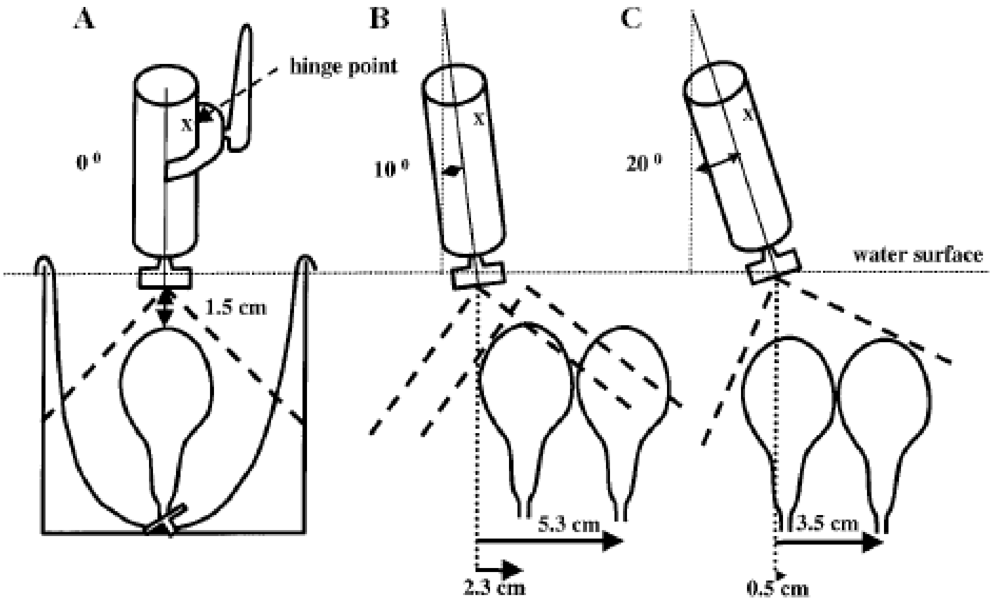
Figure 1

Experimental setup used in balloon models and autopsy hearts is shown with water bath, flexible mechanical arm, transducer, and centimeter scale attached to floor (arrow), along which the water bath was displaced.

Imaging procedure

A commercially available ultrasound system was used with a 2 to 4 MHz phased array broad band transducer (HP Sonos 5500, Agilent Technologies, Palo Alto, Calif). Imaging was performed with 3 MHz fundamental gray scale mode. The transducer was mounted in a TomTec rotational device (a metal cylinder) which was connected to a step motor (TomTec Imaging System, Munich, Germany). The latter was controlled by a steering logic, which allowed controlled rotation of the transducer after ECG gating. The probe is kept stationary by a mechanical arm and rotated within the rotational device through 180 degrees with incremental steps of 5 degrees using an ECG simulator set at 120 per minute. The respiratory gating was switched off. The step motor and the video output of the HP Sonos were interfaced with the TomTec Echo-Scan 4.1 system. Accordingly, multiple 2D images of the heart were acquired

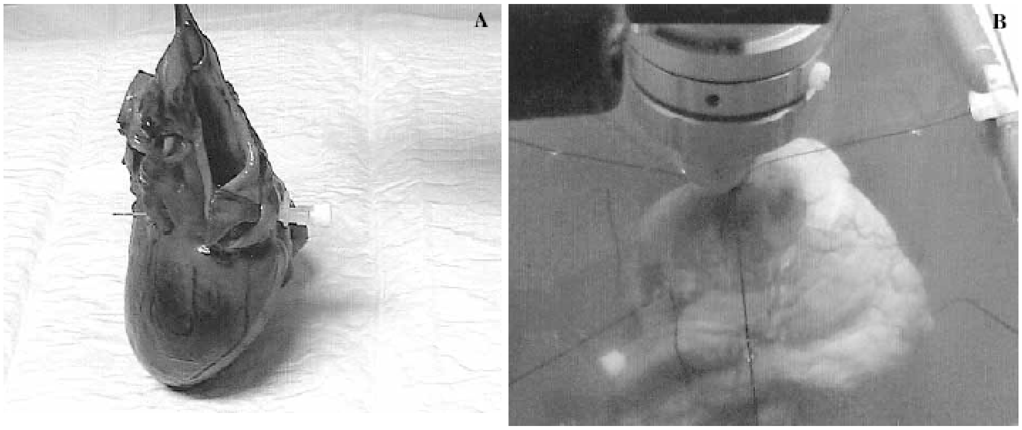
Figure 2



Schematic drawing in panels A, B, and C of method of angulation and translation. In panel A are shown: waterbath; balloon with stopcock attached to curved piece of metal for support; transducer with rotational device, attached to mechanical arm (partly visible); water surface level with transducerballoon depth 1.5 cm; and 90-degree ultrasound sector. X is hinge point (indicated by dashed arrow). Position in "0 measurement" is shown. In panel B, situation with 10-degree angulation and 2.3 to 5.3 cm translation is shown with corresponding sector and balloon positions within sector. Direction of solid arrows corresponds to direction in which water bath was moved. Theoretical second sector is shown, which would be obtained by further translation. It can be observed that in latter there is still substantial cutoff of part of apical aneurysm. Panel C shows 20-degree angulation and corresponding translation of 0.5 to 3.5 cm. Both balloon positions fit within sector/3D conical dataset

and stored on hard disk as raw data. The transducer was partially immersed into the water bath and initially positioned so that the sector encompassed the entire balloon. The flexible mechanical arm, which was attached to a table, allowed accurate tilting in a vertical plane of the transducer by 10 or 20 degrees (angulation) from its optimal position (0 degree) with the aid of a goniometer (figure 2). Horizontal displacement (translation) of the transducer relative to the balloon tip could be performed by pulling back the water bath in a controlled fashion along a centimeter scale attached to the floor. Care was taken that both tilting and horizontal displacement were performed in the same direction and in the same vertical plane (figures 1 and 2). Both aneurysmatic and nonaneurysmatic balloons of 150, 250, and 350 mL, as well as the 3 autopsy specimen volumes, were measured at 0 cm translation and without any angulation. This was considered as the “0 measurement,” which is the ideal measurement, ie, the transducer is located just above the center of the balloons’ long axis or above the apex and the long axis of the LV, and the whole volume is encompassed in the conical data set. Subsequently, the experiment consisted of 3 steps: first, translation of 1, 2, 3 and 4 cm was performed and the corresponding balloon or LV volumes were measured. Second, angulation was performed in the aneurysmatic balloons only by tilting the transducer 10 or 20 degrees, carefully maintaining the center of the transducer above the balloon’s long axis to avoid translation; and finally, the combination of translation and angulation was studied by pulling the water bath in steps of 4, 5, 6, and 7 cm from “0 measurement” and then tilting the transducer at each step by 10 or 20 degrees. The resulting volumes were measured. Because of the high hinge point of the flexible mechanical arm (as shown in figure 2) relative to the transducer surface, every form of tilting, inevitably, resulted in some translation. This was corrected by expressing the net horizontal displacement of the center of the transducer relative to the balloon tip, instead of the pulled back distance of the water bath. The reason why we started tilting from 4-cm water bath displacement onward was that at lower distances there was hardly any visible image.

Figure 3



Two autopsy hearts are shown, one outside water bath (A), and one within water bath suspended upright by strings (B). Note infusion needle, which marks mitral annulus as base of LV (A).

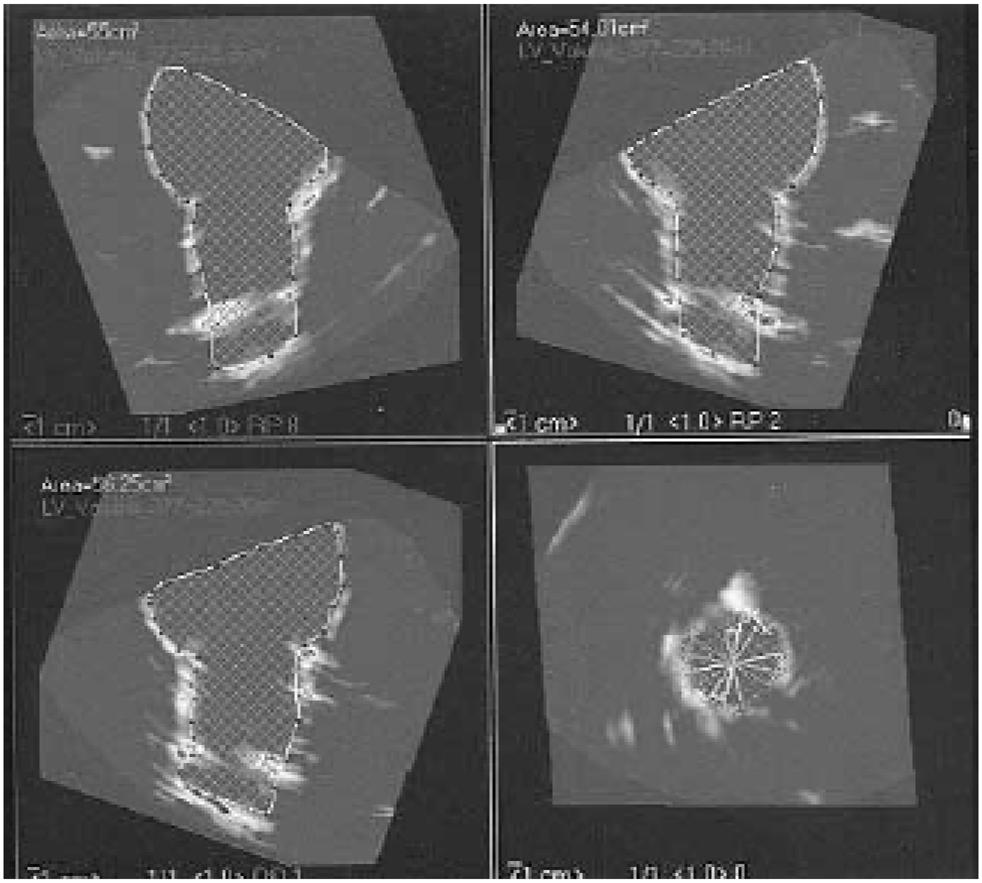
Data analysis

The volumetric conical data sets were converted and postprocessed off-line into a Cartesian coordinate system for subsequent analysis. Both postprocessing and analysis were performed on a TomTec 4.1 Echo View workstation. The LVCAP 1.0 software package (TomTec Imaging System, Munich, Germany) was used for volume calculations. The boundaries were traced by the mouse-driven cursor on the white side of the black-and-white boundary. The average rotation method with 8 slices centered on the balloon's or LV's long axis was selected (interactive spline algorithm)[10]. The traced areas of the long-axis slices were represented as pie slices in a number of variable short-axis slices from base to apex (figure 4). Each short-axis level can thus be examined and, according to its endocardial boundaries, corrections can easily be made on the long-axis slices. The volume of the entire balloon or LV was calculated by summing the corresponding long-axis pie slices.

Statistical analysis

Data are expressed as mean ± SD. Linear regression analysis was used to assess the relation between true and measured volumes. The agreement between the balloon/autopsy heart volumes and the true water volumes was expressed as the mean of the differences (bias) and the limits of agreement (± 2 SD) by Bland-Altman analysis. To analyse the differences between the different combinations of translation and angulation multiple analysis of variance (SPSS) for repeated measurements were carried out. The observations were made at 4 different translations, which can be seen as repeated measurements. Furthermore, for the nonaneurysmatic and the aneurysmatic balloons, the observations were performed for 3 different volumes (150, 250, and 350 ml); thus a correction is made for volume. The main outcome variable is the observed percentage of the true water-filled volume. In the first analysis, the 3 combinations (only translation, translation and 10-degree angulation, and translation and 20-degree angulation) were compared with each other. Because the translation and 20-degree angulation is of main interest in this study, a second analysis was carried out in which this combination is compared with the 2 other combinations (i.e., translation and translation + 10-degree angulation). For the autopsy hearts, analysis was performed in a similar way. A value of $p < 0,05$ was considered statistically significant. The repeatability of 3D echo volume measurements was expressed as a coefficient of variation (percentage of the SD of the mean of 2 sets of measurements divided by the mean of these 2 sets). In this way the intra-observer variation was expressed for the balloon volumes only (in the autopsy hearts there were too few observations).

Figure 4



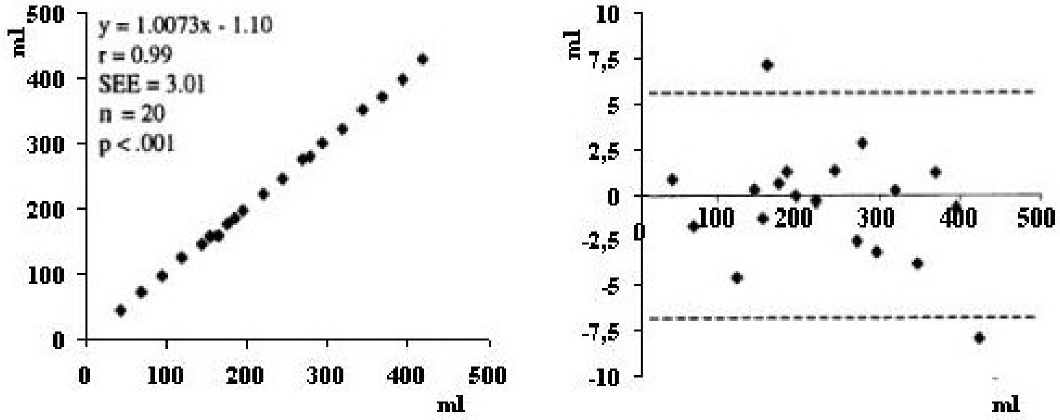
3D analysis of aneurysmatic 350-mL balloon with 10-degree angulation and 5.3-cm transducer tip distance. Note how sector cuts off a substantial part of balloon so that true volume of 350 mL was reduced to measured volume of 225 mL. Three long-axis planes and one short-axis plane are shown.

Results

Three-dimensional reconstruction was successfully performed in all balloons and autopsy hearts. The time required for data processing was 5 minutes on average and for image analysis 5 to 10 minutes. The correlation and linear regression equation between true and measured volumes of the balloons with the “0 measurement” were as follows: $r = 0,99$; $p < 0,001$; $y = 1,00x – 1,11$; SEE = 3,02 mL (figure 5). The bias and limits of agreement were

–0,5 ± 6,1 mL. Intra-observer variability obtained by measuring 20 aneurysmatic latex balloons was 2%. The effects of angulation, translation, or the combination of both are shown in figure 6 for the 3 nonaneurysmatic and the aneurysmatic-shaped balloons.

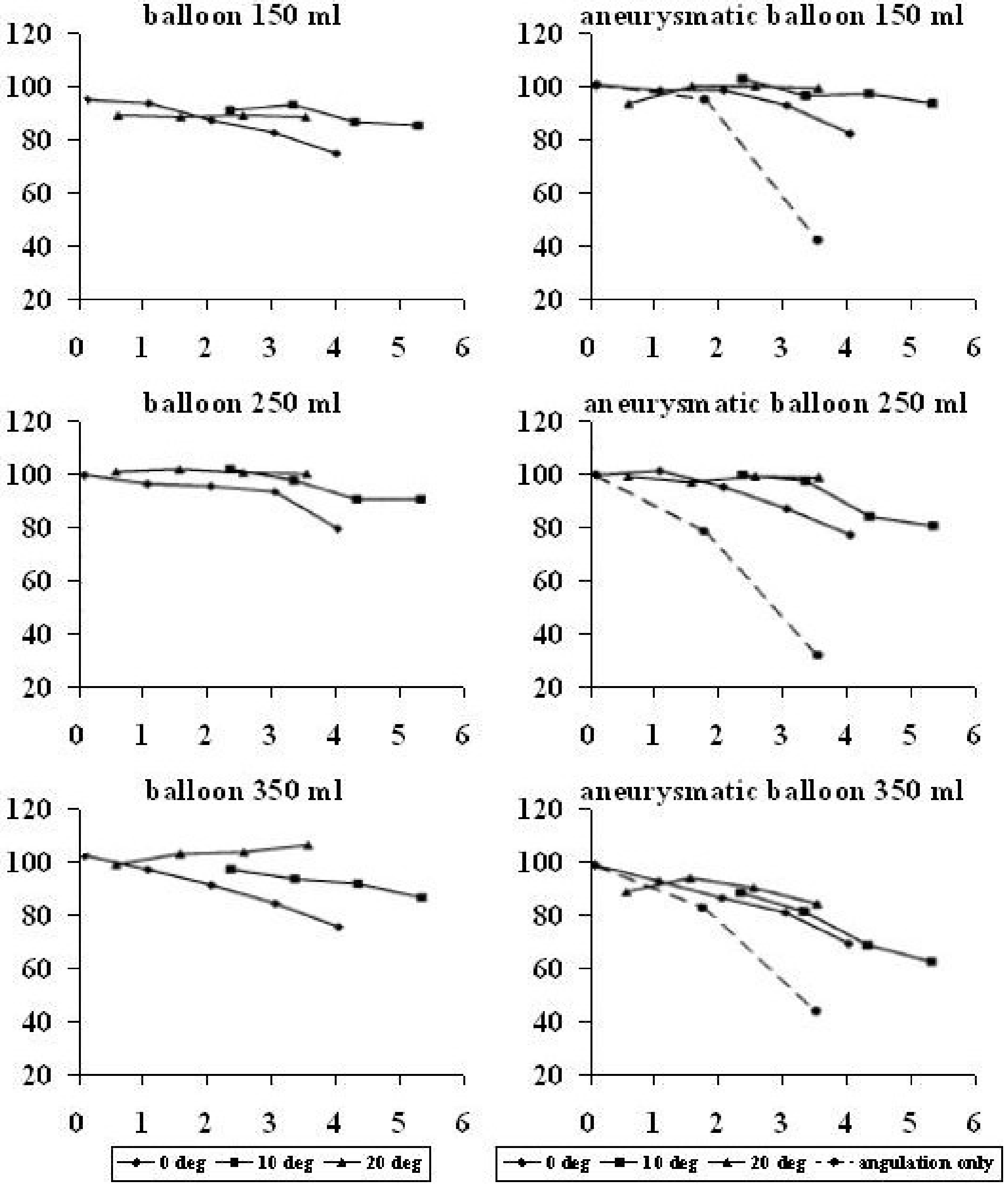
Figure 5



Linear regression (A) and Bland-Altman plot (B) of true balloon volumes versus 3D balloon volumes. Linear regression equation, its coefficient *r*, and standard error of estimate (SEE) are shown, as well as number of observations (*n*). In Bland-Altman plot, bias and 95% confidence limits are indicated.

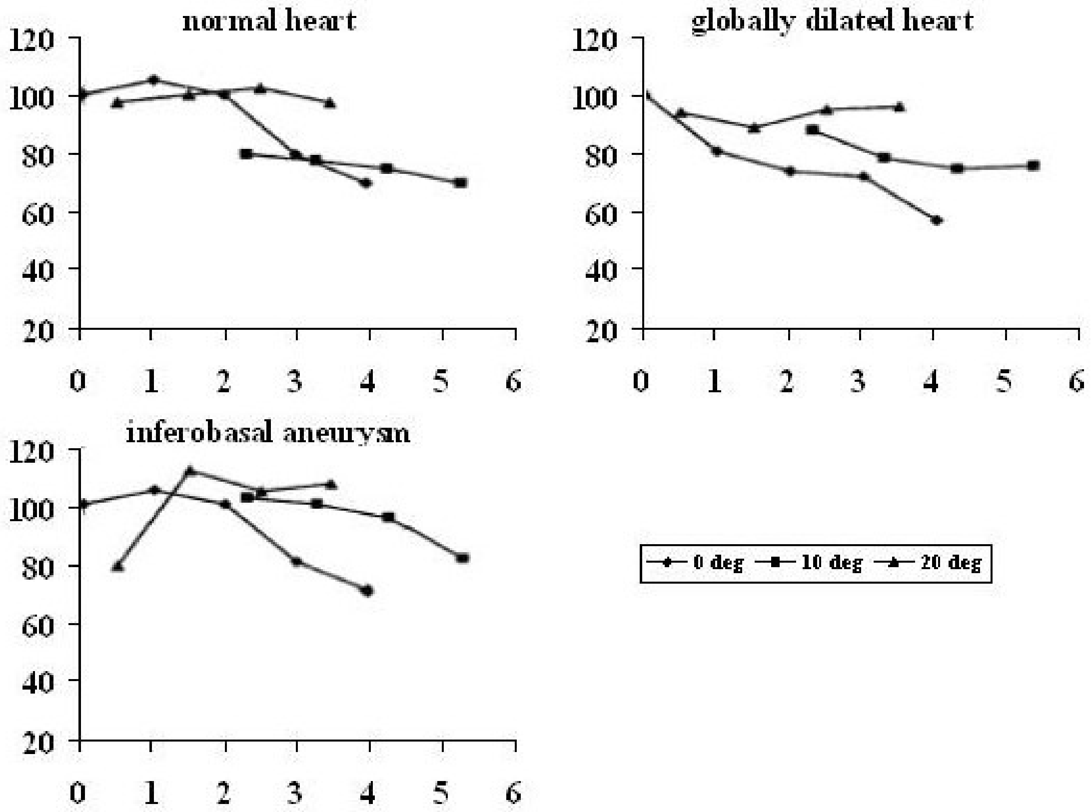
For the (non) aneurysmatic balloons of 150, 250, and 350 ml, horizontal translation of the transducer (without angulation) from 1 to 4 cm from the balloon tip caused a progressive reduction of the measured volume of up to 74% of the true volume. Angulation of 10 to 20 degrees without translation caused a reduction of the measured balloon volume of up to 80% and 34%, respectively. The combination of 10- or 20-degree angulation with progressive translation up to 5,3 and 3,5 cm, respectively, caused a reduction of the measured volume up to 64% for 10-degree angulation, whereas 20-degree angulation yielded no loss in measured volume, except in the largest 350 mL aneurysmatic balloon (loss of 15% of the true volume). Pooled analysis of the 20-degree angulation plus translation curve against the other curves was highly significant (p < 0,001).The angulation without translation curves was also significantly different (p < 0,001) from the 20-degree angulation plus translation curves, as can be seen in figure 6. Figure 7 shows the results for the 3 autopsy hearts. Similar findings and significance were observed.

Figure 6



Relative measured volumes (%) are shown for both aneurysmatic and nonaneurysmatic balloons in relation to "0 measurement volume," which was set as 100%. Curves represent translation only (diamonds), combination of translation and 10-degree angulation (squares) and combination of translation and 20-degree angulation (triangles). Y-axis scale runs from 20% to 120%. X-axis shows net displacement of center of transducer to balloon tip. For translation, this was 0 to 4 cm; for 10-degree angulation + translation, this was 2,3 to 5,3 cm; for 20-degree angulation + translation, this was 0,5 to 3,5 cm. For aneurysmatic balloons, angulation without translation is shown for 0, 10, and 20 degrees (closed circles); X-axis does not apply here: net displacement of center of transducer to balloon tip was 0.

Figure 7



Relative measured volumes (%) are shown for 3 autopsy hearts in relation to their “0 measurement” volumes. Symbols for curves are as described in figure 6. Y-axis scale runs from 20% to 120%.

Discussion

To the best of our knowledge this is the first document showing the effects of translation and/or angulation on 3D volumes obtained by rotational acquisition. The aim of our in vitro experiment was to assess accuracy of 3D volumetry and to show to what extent transducer position relative to the long axis of the balloon or LV was related to volume underestimation in “apical” 3DE with rotational acquisition, especially in dilated aneurysmatic LVs.

Accuracy

In this study, the rotational mode of acquisition proves to be a highly accurate and reproducible method for volume computation provided that the entire volume is encompassed within the conical data set. The finding in the balloon phantoms is similar to previous studies, in which the TomTec disk method algorithm with 3 mm, respectively 8 mm, slice thickness was used for volume analysis [11]. A small systematic LV volume underestimation relative to the true water volume of about 10% was shown for all 3 autopsy hearts.This is due to the ventricular trabeculae, the inner border of which was traced. The sponge-like structure of the trabeculae can explain the difference between true water volume and the measured LV volumes, which was not observed in the balloon studies [9]. The average rotation analysis mode, with at least 5 to 7 long-axis slices, has proved its accuracy compared with the traditional disk method, and is easy to use and timesaving [10,12].

Volume underestimation in balloons and autopsy hearts

Both translation and angulation alone cause a progressive reduction of the volumes compared with the optimal volume at “0 measurement.” The combination of 10-degree angulation and up to 5,3 cm translation did not prove to be better than translation alone. In contrast, 20-degree angulation and 0,5 to 3,5 cm horizontal translation, however, completely compensates for this volume underestimation by 3DE, except in the largest aneurysmatic balloon of 350 ml. Although we did not test more pronounced angulation (greater than 20 degrees) in combination with translation of greater than 3,5 cm, it is very likely that this compensation for angulation by translation is maintained in these circumstances up to a broad range of larger angles and greater than 3,5 cm of translation (figure 2). In other words, the acoustic window becomes more “parasternal” rather than “apical” as the ultrasound sector, and therefore the base of the conical data set is directed more perpendicular to the long axis of the balloon. The balloon volume, especially in the apical region, can thus be better encompassed within the conical data set. If, however, a true perpendicular or side view would be used, the balloon tip or base would almost certainly fall beyond the data set, indicating that there must be an optimal range between 20 and 90 degrees. The corresponding optimal range for translation is less critical (i.e., > 0,5 cm from the balloon tip) because the sector and conical data set diverge. The autopsy hearts were all in a postmortal systolic contraction phase [13] (the 2 hearts that were formalin fixed were even more contracted because of the fixation process), therefore the

LV volumes were rather low. The findings obtained in the autopsy heart experiment were quite similar to those of the balloon experiment with the 20-degree angulation and translation curves significantly different (almost without volume underestimation) from the other curves.

Comparison with other studies

Various techniques for 3D reconstruction and volume measurements have been developed [4-6,8,11,14,15]. They are all based on acquisition of a series of cross-sectional cut planes by random or sequential imaging. The latest development is real-time 3D imaging [16,17]. Rotational mode of acquisition has proven its value for accurate volume assessment [4,6,8]. By using the transthoracic approach, however, this mode of acquisition imposes some difficulties, as already discussed. Foreshortening and partial cutoff of an apical aneurysm or dilated LV after 3D rotational acquisition may be important limitations of this technique. Two in vitro studies have shown that the aneurysmatic parts of the LV can be accurately measured in vitro in asymmetric model hearts. All these models were positioned well within the scan sector [6,11], which is often not the case in clinical echocardiography when using the "apical" window. Notwithstanding the aforementioned limitations of 3D apical volume assessment, several clinical studies that used 3D apical rotational acquisition have shown accurate correlation with magnetic resonance imaging [4,8], or cineventriculography [6]. In clinical echocardiography, off-axis views are often unintentionally used in "apical" echocardiography because the transducer is almost never exactly located on the true anatomic apex due to tissue interposition [9]. Erbel et al [9] showed that in the 3-chamber apical view, the average transducer angulation relative to the long axis and true apex of the LV in a group of 46 patients was 22,4 ± 4,1 degrees, with translation comparable with our in vitro experiment. The relative volume underestimation in patients has been addressed earlier by Bartel et al [18], by using realtime 3D imaging through the apical window in 35 patients. In this study, however, the extent of volume underestimation due to tangential cuts was estimated, by using a hemispheric volume algorithm for calculation of the cut-off volume. The predicted calculated volume underestimation was rather low (4,3% ± 3,5% and 3,7% ± 1,9% for end-diastolic and endsystolic volume, respectively). Shiota et al [16] also used real-time 3D imaging in 34 patients, of whom the acquisition was performed intraoperatively in 15 patients. In this study a good correlation was observed with magnetic resonance imaging, except in LV end-diastolic volumes of greater than 450 ml. In both studies, however, a pyramidal data set was created instead of a conical data set. Furthermore, in the latter study, a substantial proportion of patients did not have an "apical" acquisition. Therefore, the results of our study cannot be compared or extrapolated with these studies.

Limitations

For practical purposes only a limited number of steps for angulation, translation, and their combination were measured in the experiment for a limited number of balloon volumes, balloon models, and autopsy hearts. Therefore, the optimal range of translation and angulation, by which there is no loss in volume, was not assessed directly. In vivo, however, on a curved thorax, translation may occur in both horizontal and vertical directions relative to the LV apex and long axis. Furthermore, with increasing translation and angulation, other problems such as interposition by ribs, lung or fat tissue, poor image resolution in the far lateral field, and attenuation beget important [6].

Clinical implications

Volumetry with 3D echocardiography that used the rotational mode of acquisition is highly accurate and reproducible, provided that the whole volume is encompassed within the conical data set. In clinical practice, this is the case if there is a good apical window without a very dilated aneurysmatic heart. Especially in the latter, foreshortening with subsequent volume underestimation of the LV may occur in 2DE and 3DE, even if an "apical window" was to be used. Foreshortening in 2DE can be suspected to be present if there is an unexpected abnormal shape of the apex, and an abnormally short major long axis, especially in the 2- and 3-chamber view. After postprocessing, in 3DE, the major long axis, and hence foreshortening, can be directly determined in the 3D cubical display format, in which any desired plane can be positioned to yield a 2D any plane image. This cannot be assessed, however, in real-time with the TomTec system. Our in vitro experiment shows that para-apical off-axis views obtained by angulation of 20 degrees with at least 0,5 cm translation caused no, or hardly any, foreshortening or volume underestimation with 3D rotational acquisition, even in dilated aneurysmatic hearts. Therefore, off-axis views in 3D echocardiography may be an attractive alternative for conventional "apical" imaging, if the apical window is not available. Another advantage of off-axis imaging is that imaging itself may also be improved because the angle between the transducer and the reflecting endocardium is more perpendicular, by which more backscattered energy will be returned to the transducer.

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