Comparison of Aortic Lumen Area and Distensibility Using Cine and Phase Contrast Acquisitions

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Abstract

The accuracy of the estimation of the aortic lumen area was investigated using an automated segmentation method (ART-FUN). The study included both Steady State Free Precession (SSFP) and Phase Contrast (PC) MR acquisition sequences. The precision of the segmented lumen area was tested against expert manual contouring for 860 aorta sections from three different MR scanners. Comparison of lumen areas and distensibility values obtained from both SSFP and PC sequences was also performed in a group of 50 subjects. While linear regressions indicated very similar manual and automated segmentations for SSFP and PC data (slope=1, r=0.99), the corresponding distensibility values were less correlated (slope=0.76, r=0.54).

1. Introduction

Magnetic Resonance Imaging, using either black-blood images, cine gradient echo imaging or gadolinium-enhanced angiography, is a useful tool for the assessment of cross-sectional aortic area or diameter within different segments of the aortic arch. These measurements, which reflect the risk of rupture, are crucial for the evaluation of aortic size increase during the follow-up of patients and to decide when surgery has to be performed [1].Moreover, measured at systole and diastole, these areas can also be used for the estimation of aortic stiffness indices [2].

Phase contrast (PC) imaging is currently used to estimate the pulse wave velocity (PWV), which is an excellent image of the regional aortic stiffness [3] and is useful for quantifying mechanical or genetic disorders, such as coarctation [4] or Marfan syndrome [5]. PC images with increasing spatial resolution can now be acquired during a single breath-hold and may also allow the estimation of local aortic distensibility [6].

A robust semi-automatic 2D+t segmentation method is proposed to segment both steady-state free-precession (SSFP) and phase contrast PC images. First, the accuracy of the automated segmentation is tested in terms of contour location and aortic lumen areas versus the manual contouring of two experts on a set of 12 acquisitions from three different scanners. Second, the aortic cross-sectional areas and distensibility values obtained for both FFSP and PC acquisitions are compared in the ascending and descending aorta sections of 50 healthy subjects.

2. Methods and material

2.1. Features of the aortic PC images

Segmentation of the ascending aorta must take into account its anatomic location, close to the pulmonary artery and vena cava. These two bright vascular structures can attract the aortic contour away from the aortic wall. Segmenting the descending aorta is often easier due to its location in a more homogeneous background. While these difficulties concern both SSFP and PC images, the accurate segmentation of the aorta on PC image sequences can be impaired by some additional difficulties related to uncorrected flow artifacts along the cardiac cycle. During diastole, the gray level intensity is higher in the vena cava than in the ascending aorta so that the contour is all the more attracted by the venous flow. Any systolic signal drop close to the aortic wall, related to velocity gradient or to phase dispersion in the voxel, makes the contour enter inside the arterial lumen.

2.2. Segmentation process: guidelines

To take into account the above difficulties our technique included specific features: 1) to reduce variations in intensity within the aortic lumen during the cardiac cycle, the intensity was automatically scaled; 2) to consider the coherence of the aortic wall motion during the cardiac cycle, the aortic contour was modeled by a 2D+t deformable surface (x, y, t) [7]; and 3) to avoid an attraction by a neighboring 'white' structure (e.g., the other mediastinal vessels) or a narrowing of the contour inside the aorta when flow darkens the external part of the lumen, a two-step estimation of the contour was performed. The first step was an estimation of the aortic contour based on the combined attraction of the gradient image and the black rim surrounding the aorta. The

second was a refining step for which the attraction fields were restricted inside the previously estimated contour, and the attraction to the black background was lowered to allow estimation closer to the aorta.

2.3. Initialization of the segmentation

First, the image sequence was averaged over time, resulting in a single image in which the center of the aorta was manually defined. A first 2D circular contour was then fitted by region growing and duplicated over all images of the sequence as the initial contour of the 2D+t model.

2.4. First study

The first study was designed to assess accuracy of the segmentation with respect to experts. According to aforementioned difficulties, PC acquisitions were chosen as more difficult to segment than SSFP sequences. Acquisitions were performed using three different MR scanners, the GE Excite (1.5 T), the Siemens Avanto (1.5 T), and the Siemens Magnetom Trio (3T), according to conventional ECG triggered PC protocols. For the 12 subjects the ascending and descending aorta were manually contoured by two experts along the whole cardiac cycle (resulting in a total of 860 contours). One of the two experts also performed a second manual segmentation. Moreover, each expert performed an automatic segmentation.

The imaging parameter were as follow: field-of-view: (200-480 x 280-400); repetition time:12-30ms; echo time: 3.5-4.4 ms; flip angle: 20-30°; slice thickness: 5-10 mm square voxel size: 1.1-1.87 mm; cardiac phases: 21-50, velocity encoding: 150-250 cm/sec; NEX: 1-3; inter-phase delay: 15-40 ms; number of phases: 21-50.

2.5. Second study

The second study was designed to compare lumen areas and distensibility values obtained when using SSFP and PC acquisitions. Distensibility is defined as: $Dist=(\Delta A/A_d)/\Delta P$ where $\Delta A=A_s-A_d$ is the change in luminal area over the cardiac cycle, A_s being the maximum systolic area and A_d the minimum diastolic area and where ΔP is the pulse pressure.

Fifty healthy volunteers (13 females, 37 males), asymptomatic, with age ranging from 18 to 72 years, (age=39±14 years) and without known cardiovascular disease, were examined after giving informed consent. This provided, after selection of systolic and diastolic areas in the ascending and descending aorta sections, a total of 200 lumen areas and 100 resulting distensibility values per operator and per acquisition sequence.

In healthy subjects, acquisitions were performed on a 1.5T MR system (Signa HDX, GE Healthcare, Waukesha, WI) using electrocardiogram gating and a cardiac phased-array surface coil for radiofrequency signal detection. To visualize every segment of the thoracic aorta, the entire aorta was imaged in the transverse, oblique sagital plane and coronal oblique plane by using cine-segmented ECG-gated SSFP acquisition by using three levels per breath hold. Then, one level close to an axial plane, perpendicular to both the ascending and descending aorta and proximal to the bifurcation of the pulmonary artery was acquired using the same SSFP and PC sequences. The average imaging parameters of this SSFP acquisition were as follow: repetition time: 3.2 ms; echo time: 1.4 ms; flip angle: 50°; slice thickness: 8 mm; voxel size: $0.7*0.7$ mm^2; view per segment: 12; cardiac phase: 9-100; inter-phase delay: 6-81 ms. PC acquisition parameters were as follow: repetition time: 7,3-12.4 ms; echo time: 1.4 ms; flip angle: 20°; slice thickness: 8 mm; voxel size: 1.6 mm; view-per-segment: only 2; cardiac phase: 25-85; inter-phase delay: 13-38 ms; maximal velocity encoding: 200 cm/ s.

2.6. Statistical analysis

For the first study, the Dice overlap measure [8] was computed between the 860 manual and automatic contours for each image. The mean and worst Dice measures were then computed for each subject in both ascending and descending aorta. Mean and standard deviation of these values were provided. The Inter-technique and intra-technique variability in the aortic lumen area values were calculated as the sum over all the studied slices of the absolute difference between repeated measurements in percent of their mean.

Linear regression providing slope (a), intercept (b) and Pearson coefficient (r), and Bland-Altman plots providing bias (m) and standard deviation (SD) were used to compare 1) the aortic lumen areas averaged from the three manual segmentation to the automatic lumen areas (study 1), 2) the estimated area and distensibility values obtained from SSFP and PC acquisitions (study 2).

3. Results

3.1. First study

The mean Dice overlap measure was 0.945± 0.014, the mean worst Dice overlap measure was 0.9±0.03, and among the 860 estimated Dice overlap measures, the worst of all was 0.84. In addition, the mean Dice overlap measure was similar for the three scanners (Trio: 0.946±0.016, Excite: 0.941±0.015, Avanto: 0.950± 0.008).

The calculated inter-observer variability was 10.09±8.29% for the manual segmentation, while it was only 0.59±0.92% for the automated segmentation. The intra-observer variability calculated for the manual segmentation (8.43±6.58%) was quite similar to the inter-observer variability.

3.2. Second study

For the 50 subjects, the visual control of the segmented aortic lumen was judged satisfactory by the two operators and no failure occurred in any aorta section using the automatic segmentation method. Figure 1 shows the comparison between areas and distensibility values obtained using SSFP and PC acquisitions.

The bias and standard deviations can be compared to the mean lumen area (5.44 cm^2 for the first study and 5.19 cm^2 for the second study) and the average distensibility value: 4.1×10^{-3} $mmHg^{-1}$ for SSFP and 4.6×10^{-3} $mmHg^{-1}$ for PC. While the aortic systolic and diastolic lumen areas appeared very similar using either acquisition sequence, the distensibility values were different due to the error amplification in strain calculation.
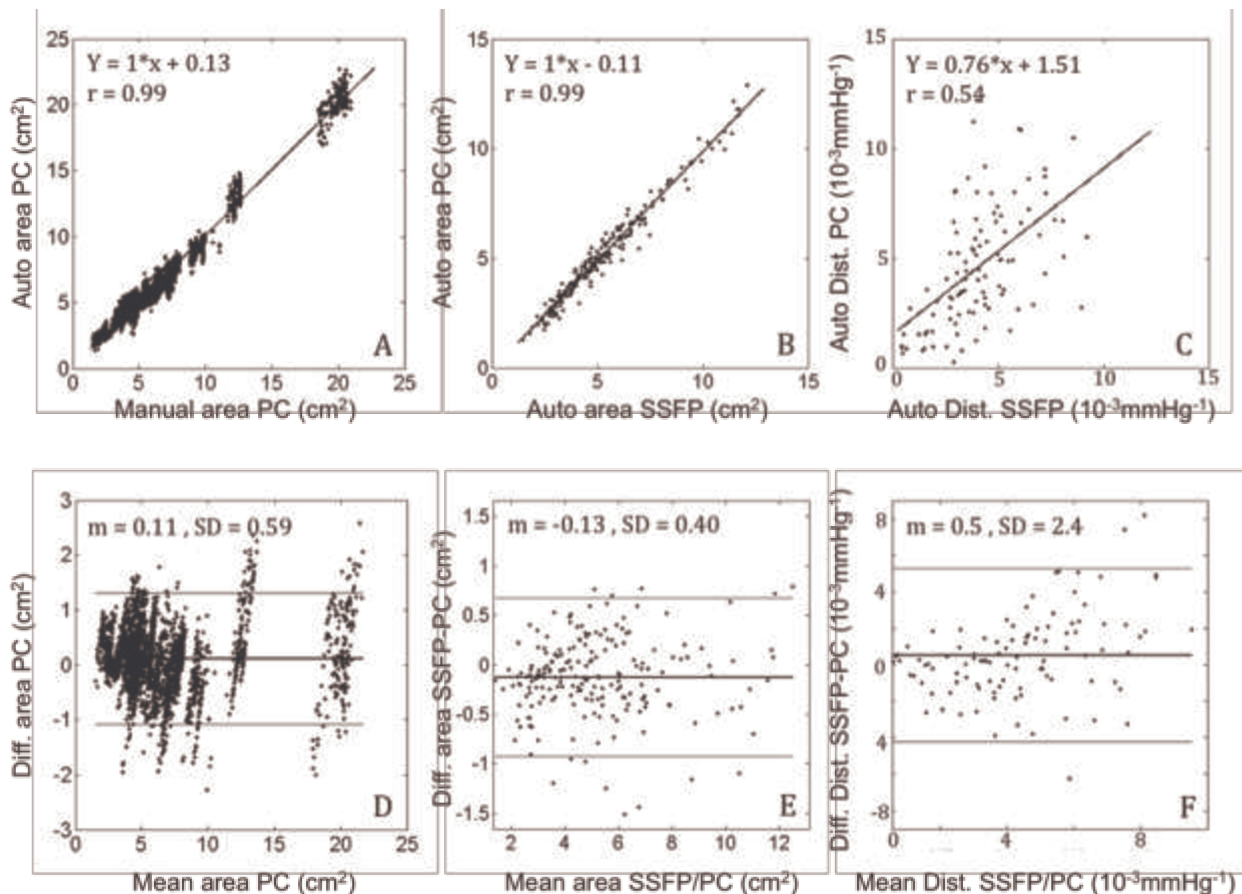

Figure 1. Comparison of automated segmentation with manual contouring: (A, D). Comparison of lumen areas (B, E) and distensibility values (C, F) obtained using SSFP and PC acquisitions sequences. Top: linear regression, bottom: Bland-Altman study.

4.   Discussion

A precise segmentation of the aortic lumen along the cardiac cycle is quite possible since a correct integration of the spatial and temporal features of the image sequence is made. In the present studies, the automatic segmentation method implemented in the ART-FUN software platform (7) dedicated to the functional analysis of the aorta was used. It provided an estimation of the lumen area very similar to manual

contouring of experimented operators. This segmentation also appeared quite independent of the MR scanner. Finally very similar lumen areas were obtained from the automated segmentation of SSFP and PC acquisitions. However, the derived distensibility values appeared very dependent on the precision obtained when segmenting the vessel lumen.

Neveretheless, the present study showed that the distensibility values obtained from either SSFP or PC acquisition sequences were in good agreement and reproducible. These value were also consistent with those proposed in previous studies: $4.3 \pm 1.3 \times 10^{-3}$ mmHg^{-1} (age 24 ± 2 years, n=10) from Lalande et al. [9], $4.41 \pm 1.94 \times 10^{-3}$ mmHg^{-1} (age 30-49 years, n=46) from Redheuil et al. [10], and $4.4 \pm 2.2 \times 10^{-3}$ mmHg^{-1} (age 32 ± 3 years, n=23) from Groenink et al. [11].

In conclusion, accurate estimates of aortic distensibility can be obtained from both SSFP and PC acquisition as long as a robust segmentation of the aortic lumen is performed throughout the cardiac cycle. Small differences can be observed between acquisition techniques mainly due to image quality or flow artifacts that can impede the segmentation process. Accurate local assessment of aortic stiffness is more often obtained from SSFP sequences than from PC sequences. However PC acquisitions are complementary to SSFP acquisitions and also give further flow information and allow accurate PWV assessment for the estimation of regional aortic stiffness.

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