Assessment of cardiac function with a three-dimensional shape model based on surface harmonics

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Introduction: The assessment of cardiac function requires the computation of left-ventricular (LV) and right-ventricular (RV) volumes, at least for the end-diastolic (ED) and end-systolic (ES) phases. This is typically done on the basis of short-axis (SA) cine acquisitions [1] by manually contouring in each slice the LV and RV endocardial and epicardial borders. Following Simpson's rule, the corresponding volumes are usually obtained as the sum of the delimited areas multiplied by the distance between the slice centres. The precision of this method can be hampered by inaccurate scan planning, motion, and partial volume effect, which all affect the localization of the valve planes, and hence, the exact determination of the most basal slice, as well as the localization of the tip of the apex [1]. Both are best visualized and localized on long-axis (LA) slices. Therefore, the functional analysis can be improved by the combination of slices acquired with different orientations. We propose to use a cardiac shape model to merge the different two-dimensional cardiac contours into a single three-dimensional representation of the ventricles, which then serves as basis to perform the functional analysis. The advantages of this method to increase reliability and to save manual processing time are discussed.

Methods: The cardiac shape model we propose consists of LV endocardial, LV epicardial, and RV endocardial surfaces. Each surface is represented with three-dimensional surface harmonics [2]. In this approach, a closed, star-shaped surface is parameterized with prolate spheroidal coordinates (η,θ,ϕ), given a coordinate centre *0* and an orthonormal basis $(\vec{i},\vec{j},\vec{k})$. The transformation between Cartesian and prolate spheroidal coordinates reads:

$$x = c\sinh(\eta)\sin(\theta)\cos(\phi),\quad y = c\sinh(\eta)\sin(\theta)\sin(\phi),\quad z = c\cosh(\eta)\cos(\theta)\ , \qquad (1)$$

where *c* is a shape parameter. Each surface is then modelled as the mapping [2]:

$$\eta(\theta,\phi) = \sum p_{l,m}\,\chi_{l,m}(\theta,\phi)\ ,\ \text{with}\ 0 \le l \le L,\quad 0 \le m < 2l+1\ . \qquad (2)$$

$\chi_{l,m}$ are prolate spheroidal harmonic functions, *L* is the degree of the decomposition, and $p_{l,m}$ are the model parameters. In order to extend this approach to the modelling of open surfaces, we propose to apply a symmetry condition: Each ventricular surface can be considered as the lower half of a closed surface that is symmetric w.r.t the valve plane. Hence, we take the centre *O* to lie on the valve plane and the vector $\vec{k}$ to be normal to the valve plane, pointing from the ventricle to the atrium. With this choice, a symmetric surface w.r.t the plane $(\vec{i},\vec{j})$ is obtained by setting $p_{l,m}=0$ if $l+(m+1)/2$ is odd in Eq. (2). The RV endocardium, which is obviously not star-shaped, can furthermore be accurately modelled by forming the convex hull of the RV endocardium and the LV endocardium: this defines a star-shaped surface that fits exactly the RV endocardium outside the LV. These two methods significantly improve the robustness of the modelling without requiring a computationally intensive re-parameterization as proposed in Ref. 3.

The fitting of the three-dimensional shape model to a set of extracted points $P_i = (\eta_i,\theta_i,\phi_i)$ is performed by computing the parameters $p_{l,m}$ that minimize the sum of the squared distances to the set of points P_i [2]. The solution to this linear least-squares problem is computed using traditional linear algebra.

A SSFP cine sequence with breath-hold was used to acquire SA (8mm slice thickness, 2 mm gap, 1.36 mm in-plane resolution) and LA slices in 11 healthy volunteers. To obtain a dense coverage of the heart, the LA slices consisted of 12 slices rotated around the LV long-axis, with a regular angular spacing of 15°. LV endocardium and epicardium, and RV endocardium, at ED and ES, were manually segmented in both SA and LA slices. The 3D shape model was fitted to the extracted contours. Five different volume computations were compared: Simpson's rule based on all SA slices (M0), 3D shape model based on all SA slices (M1a), 3D shape model based on 3 SA (one basal, one apical, and one in-between) slices (M1b), 3D shape model based on all SA and LA slices (M2a), 3D shape model based on 3 SA (same as M1b) and 1 LA slices (M2b).

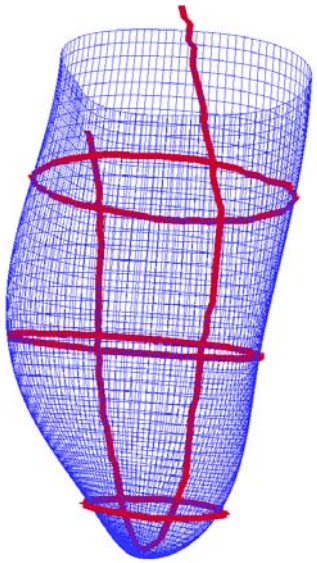

Fig. 1: Model fit of the LV endocardium (ED) in the method M2b.

M0	0.99 / 0.99 / 0.98	**M0**	0.98 / 0.96 / 0.94
M1b	0.99 / 0.99 / 0.98	**M2b**	0.99 / 0.99 / 0.99
	M1a		**M2a**

Tab. 1: Correlation between the different methods (LV endo. / LV epi. / RV endo.).

Results: First, the accuracy of the model fitting was analyzed by computing the mean square error of the fit for different values of *L*. A precision of 1.5 mm could be achieved with *L=9,* which is sufficient in view of the spatial resolution of the data. Fig. 1 shows an example of fit obtained with the method M2b. Tab. 1 summarizes the correlations between the different volume computation methods for each surface type. A regression plot for the LV endocardium is presented in Fig. 2. M0 and M1a give similar results (correlation of 0.99, regression coefficient of 0.97), which confirms the adequacy of the proposed shape model. M2a tends to produce larger volumes than M0 (correlation of 0.96, regression coefficient of 0.82), which is due to the inclusion of the LA contours that often comprise regions of the ventricles, below the valve plane and near the apex, that were missed on the SA slices. M1b and M2b reproduce well the volumes computed with M1a and M2a respectively (correlation of 0.99 in both cases, regression coefficient of 0.96 and of 1.02 respectively).

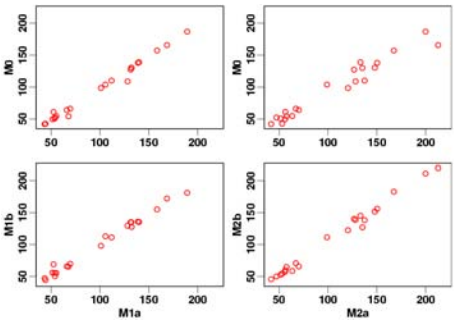

Fig. 2: Comparison of computed LV endocardial volumes (cm^3).

Discussion: Volume computation based on the Simpson's rule requires a precise planning of the SA slices and a coverage of the entire heart from base to apex. The proposed cardiac shape model allows for more flexibility in the scan acquisition: It offers the possibility to merge geometry information acquired in different orientations and, for instance, to advantageously combine SA and LA slices for a better localization of the valve planes and the tip of the apex. It also provides a suitable fit even with a reduced number of segmented contours. Moreover, shape artefacts due to motion or imperfect segmentation tend to be reduced due to the smoothing behaviour of surface harmonics. The application of the proposed shape model promises to increase the reliability of the functional analysis w.r.t inaccurate scan planning, motion, or incomplete acquisition. It can also be applied to reduce the total number of slices to be manually segmented, as demonstrated with the methods M1b and M2b, and thus to achieve significant time saving during data processing.

References:

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