TECHNICAL NOTE

Quantification of Left Ventricular Volumes from Cardiac Cine MRI Using Active Contour Model Combined with Gradient Vector Flow

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We investigated the feasibility of combining the active contour model with gradient vector flow (Snakes-GVF) to estimate left ventricular (LV) volumes from cardiac cine magnetic resonance imaging (MRI). MRI data were acquired from 27 patients, including 14 adults (9 men, 5 women, 55.0 ± 23.3 years) and 13 children (10 boys, 3 girls, 2.7 ± 2.1 years) using Gyroscan Intera (1.5 Tesla, Philips Medical Systems). LV volumes were calculated by adding the areas surrounded by the contour extracted by Snakes-GVF and compared with volumes estimated by manual tracing. Those estimated by Snakes-GVF [y (mL)] correlated well with those estimated by manual tracing [x (mL)]. In adult cases, the regression equation and correlation coefficient were $y = 1.008x - 0.517$ and 0.996, respectively. In pediatric cases, they were $y = 1.174x - 2.542$ and 0.992, respectively. In conclusion, Snakes-GVF is a powerful and useful tool for quantifying LV volumes using cardiac MRI.

Keywords: *active contour model, gradient vector flow, cardiac cine MRI, left ventricular volume*

Introduction

Cardiac cine magnetic resonance imaging (MRI) allows accurate and noninvasive measurement of left ventricular (LV) volumes. The ability to accurately and noninvasively assess LV volume and ejection fraction (EF) is essential for patient management because these parameters provide important diagnostic and/or prognostic information in patients with various cardiac diseases. Measuring LV volumes requires tracing of LV endocardial borders. However, manual tracing is not appropriate because it is time-consuming and not objective. An automatic and objective method for tracing LV contours is thus desirable. The active contour model named “Snakes”¹ has often been used as an automatic and objective method for contour extraction. Recently, gradient vector flow (GVF) has been introduced as an external force in Snakes to overcome the drawbacks of

conventional Snakes.^{2,3} We call the active contour model that uses GVF as its external force “Snakes-GVF.” We investigated the usefulness of the Snakes-GVF model in estimating LV volumes from cardiac cine MRI.

Materials and Methods

MRI protocol and patients

MRI images were acquired using Gyroscan Intera (1.5T, Philips Medical Systems, Best, The Netherlands). As a pulse sequence, steady-state free precession (balanced-TFE) was used. The acquisition parameters were as follows: repetition time (TR) = 3.8 ms, echo time (TE) = 1.9 ms, flip angle (FA) = 60 degrees, matrix size = 512×512 or 256×256 , and slice thickness = 6 mm. The number of phases in an R-R interval ranged from 15 to 25. The phase interval was approximately 30 ms in adult cases and 23 ms in pediatric cases.

We used MRI data from 27 patients, including 14 adult cases (9 men, 5 women, 55.0 ± 23.3 years) and 13 pediatric cases (10 boys, 3 girls, 2.7 ± 2.1 years).

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In adults, heart rates ranged from 55 to 96 beats per minute (bpm), and the mean $\pm$ standard deviation (SD) was 72.5 ± 15.7 bpm, and in children, heart rate ranged from 91 to 107 bpm, and the mean $\pm$ SD was 101.0 ± 7.1 beats per minute. Informed consent was obtained from each patient after a detailed explanation of the purpose of the study and scanning procedures. The slices of the heart excluding the tip and terminal areas were used in this study.

Snakes-GVF

Snakes, a pioneering framework introduced by Kass's group,¹ is the basis of a significant boundary-driven image segmentation technique. A traditional Snakes is a curve, $X(s) = [x(s), y(s)]$, $s \in [0, 1]$, that moves through the spatial domain of an image to minimize the energy functional¹

$$E = \int_0^1 \frac{1}{2} [\alpha |X'(s)|^2 + \beta |X''(s)|^2] + E_{ext}(X(s)) ds, \quad [1]$$

where α and β are weighting parameters that control the Snakes' elasticity and rigidity, respectively. $X'(s)$ and $X''(s)$ denote the first and second derivatives of $X(s)$ with respect to s . The elasticity force controlled by α acts to keep the curve from stretching. Larger values of α make the contour more difficult to stretch along its length. On the other hand, the rigidity force controlled by β acts to keep the curve from bending too much, for example, when turning a corner. Larger values of β make the curve stiffer or more difficult to bend. The external energy functional E_{ext} in Equation [1] is derived from the image such that it takes on smaller values at the features of interest, such as boundaries. This model refers to an energy minimization approach that seeks the lowest potential of a curve-based objective function. This function is a compromise between a boundary image-driven attraction term and a term that accounts for the desired internal properties of the curve.

GVF is defined as the vector field $\bar{v}(x, y)$ at position (x, y) that minimizes the external energy functional E_{ext} ^{2,3}

$$E_{ext} = \iint (\mu \cdot |\nabla \bar{v}(x, y)|^2 + |\nabla f(x, y)|^2 \cdot |\bar{v}(x, y) - \nabla f(x, y)|^2) dx dy, \quad [2]$$

where ∇ denotes the gradient operator and $f(x, y)$ is an edge map derived from the image $I(x, y)$, having the property that it is larger near the image edges. In this study, before generating the edge map $f(x, y)$ from the image, $I(x, y)$, $I(x, y)$ was processed by a 2-dimensional Gaussian filter $G_\sigma(x, y)$ with a standard deviation σ to reduce statistical

noise.^{2,3} Thus, $f(x, y)$ is given by

$$f(x, y) = |\nabla(G_\sigma(x, y) * I(x, y))|, \quad [3]$$

where $*$ is the convolution operator.

As known from Equation [2], when $\nabla f(x, y)$ is small, the energy is dominated by the sum of the squares of the partial derivatives of the vector field, yielding a slowly varying field. On the other hand, when $\nabla f(x, y)$ is large, the second term dominates the integrand, and is minimized by setting $\bar{v}(x, y) = \nabla f(x, y)$. This produces the desired effect of keeping $\bar{v}(x, y)$ nearly equal to the gradient of the edge map when it is large, but forcing the field to be slowly varying in homogeneous regions. The parameter μ in Equation [2] is a regularization parameter governing the tradeoff between the first term and the second term in the integrand.

The Snakes-GVF was solved numerically by discretization and iteration in identical fashion to the traditional Snakes.¹ The numerical implementation of GVF is described in Reference 2.

In this study, α and β in Equation [1] and μ in Equation [2] were taken as 0.1, 1, and 0.1, respectively. The parameter σ in Equation [3] was taken as 1 pixel. The number of iterations was taken as 80.

Measurement of LV volumes

We measured LV volumes as follows. The endocardial contours of LV were traced on short-axis slices in end-diastolic and end-systolic phases using Snakes-GVF. We also traced them manually and carefully for comparison. In the present study, papillary muscles were excluded from manual tracings of the endocardial contours of LV. The LV areas were then measured and LV volumes calculated by adding the LV areas and multiplying by the slice thickness. End-diastolic volumes (EDV) and end-systolic volumes (ESV) were determined as the maximum and minimum volumes during the cardiac cycle and were used to calculate the ejection fraction (EF) as $(EDV - ESV) / EDV \times 100$ (%).

Statistical analysis

Linear regression analysis was performed to analyze the correlations between the LV volumes estimated by Snakes-GVF and manual tracing and between those estimated by Snakes-GVF and conventional Snakes, and the regression equation and correlation coefficient were calculated. Bland-Altman analysis⁴ was also performed to analyze the relationship between the LV volumes estimated by the 2 different methods.

Results

Figure 1 shows an example of (a) cardiac cine

Fig. 1. Example of (a) cardiac cine magnetic resonance image, (b) gradient vector flow (GVF) field shown by arrows, (c) the contour extracted by the active contour model combined with gradient vector flow (Snakes-GVF) superimposed on the original image, and (d) the contour extracted by the conventional active contour model (Snakes) superimposed on the original image. In Fig. 1b, the contour extracted by Snakes-GVF is also shown by solid line.

MRI image, (b) GVF field shown by arrows, (c) the LV contour extracted by Snakes-GVF superimposed on the original image, and (d) the LV contour extracted by manual tracing superimposed on the original image.

Linear regression and Bland-Altman analyses were performed to compare statistically the LV volumes estimated by Snakes-GVF with those estimated by manual tracing. Figure 2 shows the results of linear regression, and Fig. 3 of Bland-Altman analyses. The closed and open symbols represent EDV and ESV, respectively. In Figs. 2 and 3, (a) and (b) show the adult and pediatric cases, respectively. As shown in Fig. 2, the LV volumes estimated by Snakes-GVF [y(mL)] showed excellent correlation with those estimated by manual tracing [x(mL)]. In adult cases, the regression equation and correlation coefficient were $y = 1.008x - 0.517$ and 0.996, respectively (Fig. 2a). In pediatric cases, they were $y = 1.174x - 2.542$ and 0.992, respectively (Fig. 2b). Bland-Altman

analysis depicted no significant biases with narrow limits of agreement for LV volumes in both adult and pediatric cases (Figs. 3a and 3b).

We also calculated the regression equation and correlation coefficient between the EF values estimated by Snakes-GVF [y(%)] and those estimated by manual tracing [x(%)] for adult (Fig. 4a) and pediatric cases (Fig. 4b). They were $y = 1.006x - 0.780$ and $r = 0.987$ for adult cases (Fig. 4a), and $y = 0.963x + 1.051$ and $r = 0.974$ for pediatric cases (Fig. 4b). Figures 5a and 5b show the results of Bland-Altman analysis of EF for adult and pediatric cases, respectively. As in Fig. 3, there were no significant biases with narrow limits of agreement in both adult and pediatric cases (Figs. 5a and 5b).

For comparison, we also performed linear regression and Bland-Altman analyses to statistically compare the LV volumes estimated by Snakes-GVF with those estimated by conventional Snakes. Figures 6 and 7 show the results of linear

Fig. 2. Correlation between the left ventricular (LV) volumes estimated by Snakes-gradient vector flow (GVF) and those estimated by manual tracing for (a) adult and (b) pediatric cases. The closed and open symbols represent the end-diastolic (EDV) and end-systolic volumes (ESV), respectively.

Fig. 3. Bland-Altman plot between the left ventricular (LV) volumes estimated by Snakes-gradient vector flow (GVF) and those estimated by manual tracing for (a) adult and (b) pediatric cases. The closed and open symbols represent end-diastolic (EDV) and end-systolic (ESV) volumes, respectively.

regression and Bland-Altman analyses, respectively. The closed and open symbols represent EDV and ESV, respectively. In Figs. 6 and 7, a and b show the adult and pediatric cases, respectively. Although there were good correlations between the LV volumes estimated by Snakes-GVF [x (mL)] and those estimated by conventional Snakes [y (mL)], the LV volumes estimated by conventional Snakes were considerably underestimated compared to those estimated by Snakes-GVF (Fig. 6). The regression equation and correlation coefficient were $y = 0.495x + 2.301$ and 0.932, respectively, in adult cases (Fig. 6a), whereas they were $y = 0.637x + 1.551$ and 0.912, respectively, in pediatric cases (Fig. 6b).

Discussion

We investigated the feasibility of calculating LV volumes using Snakes-GVF in comparison with manual tracing as a gold standard. Our results demonstrated that Snakes-GVF allowed automatic and objective contour extraction of LV and could estimate LV volumes with almost the same accuracy as manual tracing.

To investigate the effectiveness of the GVF field, we compared the LV volumes estimated by Snakes-GVF with those estimated by conventional Snakes. As shown in Fig. 6, the LV volumes estimated by conventional Snakes were considerably underestimated compared to those estimated by Snakes-

Fig. 4. Correlation between the ejection fraction (EF) values estimated by Snakes-gradient vector flow (GVF) and those estimated by manual tracing for (a) adult and (b) pediatric cases.

Fig. 5. Bland-Altman plot between the ejection fraction (EF) values estimated by Snakes-gradient vector flow (GVF) and those estimated by manual tracing for (a) adult and (b) pediatric cases.

Fig. 6. Correlation between the left ventricular (LV) volumes estimated by Snakes-gradient vector flow (GVF) and those estimated by the conventional Snakes for (a) adult and (b) pediatric cases. The closed and open symbols represent end-diastolic (EDV) and end-systolic (ESV) volumes, respectively.

Fig. 7. Bland-Altman plot between the left ventricular (LV) volumes estimated by Snakes-gradient vector flow (GVF) and those estimated by the conventional Snakes for (a) adult and (b) pediatric cases. The closed and open symbols represent end-diastolic (EDV) and end-systolic (ESV) volumes, respectively.

GVF. As pointed out by Xu and associates,³ there are 2 drawbacks in conventional Snakes. First, the initial contour must, in general, be close to the true boundary, or it will likely converge to the wrong result. Second, active contours have difficulty progressing into boundary concavities. In contrast, Snakes-GVF has a large capture range, enabling initialization of the active contour far from the desired boundary.^{2,3} Snakes-GVF also tends to force active contours into boundary concavities, where conventional Snakes has poor convergence.^{2,3} The results shown in Fig. 6 appear to indicate that the GVF field is effective for improving the above drawbacks of conventional Snakes.

As previously described, the parameters α , β , μ , and σ in Snakes-GVF were taken as 0.1, 1, 0.1, and 1 pixel, respectively. These values were determined empirically by numerical experimentation. In addition, Snakes-GVF typically provided convergent results after approximately 80 iterations. Because the parameters used in this study worked very well for a wide variety of clinical studies, we believe that this selection can be widely applied to cardiac cine MRI, making Snakes-GVF practical for routine clinical use. However, further investigations into the optimal selection of parameters will be necessary.

Recently, the level set method has been used for medical image segmentation.⁵ The basic premise of the level set method in extracting regions is to allow the initial surface of a smooth, closed object to

move along its normal vector field with speed function.⁶ The level set method is used to account for automatic topology adaptation, and it provides the basis for a numerical scheme used in geometric deformable models.⁶ Thus, it will be interesting to compare Snakes-GVF and the level set method, and this will be the subject of a future study.

In conclusion, Snakes-GVF is a powerful and useful tool to quantify the LV volumes using cardiac MRI.

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