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Automated septum thickness measurement—A Kalman filter approach

Sten Roar Snare[a,*], Ole Christian Mjølstad[a,c], Fredrik Orderud[b], Håvard Dalen[a,d], Hans Torp[a]

[a] Department of Circulation and Medical Imaging, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[b] GE Vingmed Ultrasound, Oslo, Norway
[c] Department of Cardiology, St. Olavs University Hospital, Trondheim, Norway
[d] Levanger Hospital, Nord-Trondelag Health Trust, Levanger, Norway

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ABSTRACT

Interventricular septum thickness in end-diastole (IVSd) is one of the key parameters in cardiology. This paper presents a fast algorithm, suitable for pocket-sized ultrasound devices, for measurement of IVSd using 2D B-mode parasternal long axis images.

The algorithm is based on a deformable model of the septum and the mitral valve. The model shape is estimated using an extended Kalman filter.

A feasibility study using 32 unselected recordings is presented. The recordings originate from a database consisting of subjects from a normal healthy population. Five patients with suspected hypertrophy were included in the study. Reference B-mode measurements were made by two cardiologists.

A paired *t*-test revealed a non-significant mean difference, compared to the B-mode reference, of (mean ± SD) 0.14 ± 1.36 mm (p = 0.532). Pearson's correlation coefficient was 0.79 (p < 0.001). The results are comparable to the variability between the two cardiologists, which was found to be 1.29 ± 1.23 mm (p < 0.001). The results indicate that the method has potential as a tool for rapid assessment of IVSd.

1. Introduction and literature

With the advent of pocket-sized and low cost ultrasound devices, new and less experienced user groups are expected. For the less experienced ultrasound user, automation is likely to improve the robustness and repeatability of the clinical measurements.

The interventricular septum wall thickness in end-diastole (IVSd) is a frequently used measurement in echocardiography. In arterial hypertension, left ventricular hypertrophy (LVH) is associated with increased risk of both cardiovascular morbidity and mortality [1]. The American Society of Echocardiography [2] mentions the septal and posterior wall thickness alone as a an easy way to detect LVH. The guidelines [2] suggest a normal range for IVSd of 0.6–0.9 cm for women and 0.6–1.0 cm for men. A septum is considered moderately abnormal when IVSd is measured between 1.3–1.5 cm for women and 1.4–1.6 cm for men. Measurements above these values are considered severely abnormal.

* *Corresponding author at*: Department of Circulation and Medical Imaging, PO Box 8905, Med. Tech Research Centre, N-7491 Trondheim, Norway. Tel.: +47 728 28090.
E-mail address: sten.r.snare@ntnu.no (S.R. Snare).
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Current guidelines [2], recommend a parasternal long axis view in combination with 2D B-mode or 2D targeted M-mode when measuring IVSd. The measurement should be made at the level of the mitral valve leaflet tips. Targeted M-mode has the advantage that it is easier to separate the septum from other structures such as the moderator band, tricuspid apparatus or false tendons. On the other hand, it can sometimes be difficult to place the M-mode cursor exactly perpendicular to the septum, especially for untrained users. The image in 2D B-mode is visually more intuitive than the M-mode, but the septal border can be blurred or completely missing in single frames. On several pocket-sized devices, M-mode is not available, leaving 2D B-mode as the only option.

This work aims to present a fast, automated lightweight system for IVSd measurement, suitable for pocket-sized systems. Among the few publications on this topic is a study by Moladoust et al. [3] that published a semi-automatic approach using an adaptive thresholding algorithm. The motivation for automating the IVSd measurement is to:

- Ease operation of pocket-sized systems, where manual image measurements are unpractical
- Get more consistent results when the system is operated by less experienced personnel

In this paper, the algorithm is first described in detail. Then, the results from a feasibility study are presented and discussed.

2. Materials and method

The proposed algorithm is based on contour tracking in 2D B-mode images using coupled Non-Uniform Rational B-spline (NURBS) models and an extended Kalman filter. The tracking scheme is based on the method proposed in [4]. Deformable model segmentation using a Kalman filter framework has been previously published in [5–8]. We take the approach one step further by combining several parametric NURBS contours in a hierarchy. The algorithm enables the use of information from several frames when doing septum segmentation, thus making the algorithm less sensitive to the image quality in the end-diastolic (ED) frame. The system is implemented in C++ and uses Matlab (v2008a, The Mathworks Inc.) for model design. The system loads raw ultrasound beam data from dicom files and uses an in-house scan converter to create cartesian images.

2.1. *Deformable model*

The algorithm utilizes a deformable model of the interventricular septum and the mitral valve. The recording is assumed to be a standard parasternal long-axis view. The deformable model is constructed using four NURBS curves which are *coupled* using geometric transforms. A NURBS curve is a generalization of the commonly used non-rational B-spline. It has the advantage of being linear in its parameters and is thus suitable for parameter estimation. In addition, using NURBS instead of regular B-splines offers more flexibility for shape preservation in the model. A thorough description of NURBS is found in [9]. A point on a k'th degree NURBS curve is denoted as $\mathbf{p}_l(u)$ and found by:

$$\mathbf{p}_l(u) = \frac{\sum_{i=0}^{n} N_{i,k}(u) w_i \mathbf{q_i}}{\sum_{i=0}^{n} N_{i,k}(u) w_i}, \quad u_{low} \leq u \leq u_{high} \tag{1}$$

$N_{i,k}(u)$ are the k'th-degree B-spline basis functions, $\mathbf{q_i}$ are the spline control points and w_i are the weights assigned to each control point. u_{high} and u_{low} are upper and lower bounds for the parametric coordinate, u. The rational basis functions are defined as:

$$b_{i,k}(u) = \frac{N_{i,k}(u) w_i}{\sum_{j=0}^{n} N_{j,k}(u) w_j}, \quad u_{low} \leq u \leq u_{high} \tag{2}$$

which allow us to write:

$$\mathbf{p}_l(u) = \sum_{i=0}^{n} b_{i,k}(u) \mathbf{q_i}, \quad u_{low} \leq u \leq u_{high} \tag{3}$$

The basis functions are defined on the knot vector:

$$U = u_{low}, \ldots, u_{low}, u_{k+1}, \ldots, u_{m-k-1}, u_{high}, \ldots, u_{high} \tag{4}$$

The knot vector has been chosen such that $u_{low} = 0$, $u_{high} = 1$ and $u_{k+1}, \ldots, u_{m-k-1}$ are uniformly distributed.

The complete model consists of four submodels. There is one submodel for the left ventricle (LV) side of the septum, one for the right ventricle (RV) side, one for the aortic outlet (AO) tract and one for the mitral valve (MV) leaflet. The submodels are designed using Matlab (v2008a, The MathWorks, Inc.), and they are updated by adjusting a subset of the control points.

The complete model is found by rotating (Rz), scaling (S) and translating (Tx, Ty) the submodels relative to each other using basic two-dimensional geometric transforms [10]. We denote the similarity transforms, allowing both rotation, scale and translation, by $\mathcal{T}$. Four similarity transforms are used. These are the LV side transform ($\mathcal{T}_{LV}$), RV side transform ($\mathcal{T}_{RV}$), MV transform ($\mathcal{T}_{MV}$) and mitral valve leaflet (MVL) transform ($\mathcal{T}_{MVL}$). These transforms are arranged in a hierarchy, see Fig. 1. The combined geometric transformations can be written as:

$$\begin{aligned}
\mathbf{p}_{LV}(u) &= \mathcal{T}_{LV}(\mathbf{p}_{l,LV}(u)) \\
\mathbf{p}_{RV}(u) &= \mathcal{T}_{LV}(\mathcal{T}_{RV}(\mathbf{p}_{l,RV}(u))) \\
\mathbf{p}_{AO}(u) &= \mathcal{T}_{LV}(\mathcal{T}_{MV}(\mathbf{p}_{l,AO}(u))) \\
\mathbf{p}_{MV}(u) &= \mathcal{T}_{LV}(\mathcal{T}_{MV}(\mathcal{T}_{MVL}(\mathbf{p}_{l,MV}(u))))
\end{aligned} \tag{5}$$

where $\mathbf{p}(u)$ represents a point on the final contour and $\mathbf{p}_l(u)$ a point on the contour, prior to the transformations.

The initial points on the submodel contours, prior to application of transforms, are found using the initial control points, $\mathbf{q}_{0,i}$, and (3). The complete initial model is configured by manually tuning the transforms in (5). The left screenshot in Fig. 2 shows how the four models are connected, and how the transforms have been used to orient the models to an initial shape.

Some of the transform parameters are also used as variables in the segmentation scheme, as indicated in Fig. 1. This ensures that the different models are allowed to move and scale relative to each other during tracking. As an