Original Article

Estimation of Septal Wall Thickness by Processing Sequential Echocardiographic Images

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Background: Non-invasive quantitative analysis of the heart wall thickness is a fundamental step in diagnosis and discrimination of heart disease. Thickness measurements in 2D echocardiographic images have many applications in research and clinic for assessment of wall stress, wall thickening and viability parameters. The measurement of interventricular septum wall thickness by conventional manual method is more dependent on sonographer's experiment.This encouraged researchers to develop a semi-automatic computer algorithm to access interventricular septum segments thickness.
Patients and Methods: We proposed and developed a computerized algorithm for wall thickness measurements in 2D echocardiographic image frames. In this program, wall thickness measurement is based on intensity profile function and adaptive bilateral thresholding operation. For validation, thicknesses of septum base and mid segments were estimated in constituent image frames using proposed technique followed by comparing them with conventional manual results from same images of the cardiac cycle by statistical methods.
Results: In our sample image frames (240 corresponding segments; with different range of image quality), a bias of 0.10 mm and 0.12 mm with SD differences of ±0.81 mm and ±0.72 mm and correlation coefficients of 0.87 and 0.89 were found in base and mid segments, respectively. Interobserver variability using the computer-assisted method (CAM) and conventional manual technique (CMM) were 4.0% and 4.7% for the basal and 2.8% and 3.9% for the middle segments.
Conclusion: The method introduced in the present study permits precise thickness assessment of base and mid segments of the interventricular septum wall with high concordance with CMM

Key words*:* Echocardiography, Interventricular Septum, Wall Thickness, Intensity Profile

Introduction

Cardiovascular diseases are a major health concern world-wide. Since 1980, ultrasonic imaging of the heart from multiple tomographic planes with two dimensional (2D) echocardiography led to the development of additional quantitative and qualitative methods.[1] Nowadays echocardiography has become one of the most commonly used diagnostic techniques, applicable to the assessment of a wide variety of the heart diseases.[2-6] In recent years, computer and electronic techniques have been increasingly applied to echocardiography. The augmented capability and flexibility attendant with the utilization of this technology have been fruitfully utilized in all aspects of 2D echocardiography,

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including image acquisition, manipulation and storage within the echocardiography, as well as to quantitative analysis of echo data using off-line systems.[7,8] The quantitative analysis of the heart walls thickness in echocardiographic images is a fundamental step in assessment and discrimination of the heart disorders such as ischemic heart disease, hypertrophic cardiomyopathy, mitral stenosis, restrictive cardiomyopathy[9,10] and so on. It should be noted that wall thickness measurements are small in value and suffer from observer's errors, in addition to the fact that manual measurements are more dependent on sonographer's experiment[11] that involves considerable variability. Therefore, a computer-based analysis is highly desirable to obtain more objective and quantitative.

Measurement of changes in the thickness of the arterial and heart wall over time may allow not only the evaluation of the viability, wall stress and wall thickening but could also be used to study the effect of therapeutic methods to prevent or control the heart disease.[12-14] Beach et al[15] used intensity profile technique for measurement of superficial femoral artery wall thickness using ultrasound imaging and Pignoli et al[16] related the distance between two echogenic structures in the normal arterial wall to the sum of the intima-media thicknesses. Heart wall boundaries are imaged in echocardiograms as intensity edges which are points where the image intensity changes from one level to another. So early researchers used Sobel operator and approximation of the Laplacian operator to process echocardiographic images and then to establish the threshold of the gradient magnitude map. Duan et al[17] and Mokhtari et al[18] used optical flow correlation to predict the position of the detected edges in the sequential multiframe. Optical flow tracking refers to the computation of the displacement field of objects in an image, based on the assumption that the intensity of the object remains constant. In this context, motion of the object is characterized by a flow of pixels with constant intensity. Also there are many reports describing the application of active contour or snake to heart ultrasound. The approach was first proposed by Kass et al[19] to split the contour of objects in 2-D images. Snakes, or active contours, are curves defined within an image domain that can move under the influence of internal forces coming from within the curve itself and external forces computed from the image data. The internal and external forces are defined so that the snake will conform to an object boundary or other desired features within images.[20]

In this study, we concentrated on ubiquitous 2D echocardiography, which is the most widely used imaging method to assess the heart function. The techniques proposed for wall thickness measurement cannot be applied directly; as the specific features of echocardiographic data especially the signal-to-noise ratio is relatively low and inhomogeneous. Therefore, we hereby present a computerized algorithm for regional border recognition and information on the thickness of the septum base and mid-region in 2-D echocardiographic images. Our approach relied on intensity profile drawing in septum regions manually and the automatic processing of the resulting intensity profile.

Patients and Methods

In the present study, we designed a new computerized algorithm which was used to measure interventricular septum wall thickness in 2D echo images throughout the cardiac cycle, in base and mid segments. This method is based on tracking of the heart walls echogenicity, ventricle-atrium interface. Heart wall edges in 2D echo images are regions in which image intensity change significantly so that the image in the wall regions has a higher density and in the ventricles and atriums displays brightness with lower density (Fig 1a). In this research, septum wall thickness measured by using intensity profile technique (by improfile function) of Matlab7.0.4 image processing toolbox (Math software Co., Mathwork, USA) and Thresholding technique. Assuming an intensity profile f can take K possible levels 0, 1, 2,…, K-1. Define an integer threshold, T, that lies in the range of $T \in \{0, 1, 2, \ldots, K-1\}$ The process of thresholding is a process of comparison: each pixel value in f is compared to T. Based on this comparison; a decision is made that defines the value of the corresponding pixel in an output intensity profile g(n):[21]

$$g(n) = \begin{cases} 0 \text{ if } f(n) \geq T \\ 1 \text{ if } f(n) < T \end{cases} \qquad (1)$$

We carried out proposed computer algorithm in Matlab7 software, with subsequent assessment of the measurement accuracy of 2D echocardiographic images.

Echocardiographic Data Acquisition

Echocardiography studies were performed using a Vivid7 GE echocardiography System (GE, Milwaukee, Wisconsin, USA) with an ergonomically-designed M3S transthoracic sector transducer (1.5-4 MHz). 2D echocardiographic images were obtained as a multiframe movie of 12 healthy participating volunteers (mean age 52±6.5y) using standard four-chamber view according to guide lines of the American Society for Echocardiography.[22] The images with 50 frames per second were saved as a digital recording (with AVI format) at three cardiac cycles with simultaneous electrocardiographic recorded images transferred to a Pentium4 personal computer for analysis.

Image Analysis: To examine the application of presented method to sample images, first, we designed a simple program by using the Matlab software functions for converting AVI images to constructed gray scale frames and saved them as Bitmap single frame images (Fig.1a).

(a) (b)

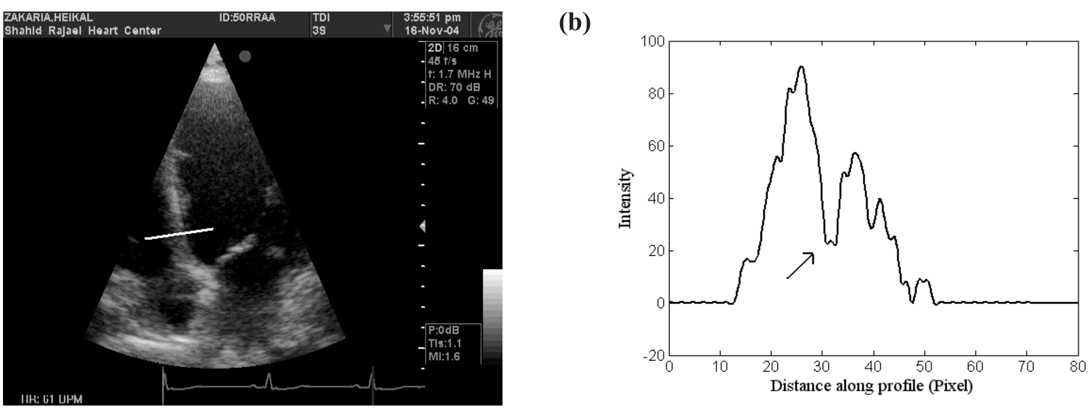

Figure 1. (a): The line profile is drawn in septum basal segment of a 2D echocardiographic image frame and (b): The intensity profile and a gross change in data values along septum wall (black arrow).

For improving the quality of images, we used histogram equalization (Image Adjust Function) such that 1% of image data is saturated at low and high intensities of images. The idea behind it extends that not only should an image fill the available gray-scale range, but it should be uniformly distributed over that range (flat histogram). There are good mathematical reasons for regarding a flat histogram as a desirable goal. For an image containing N×M pixels, the normalized image histogram is given by:[21]

$$g(n) = \begin{cases} 0 & \text{if} \quad f(n) \geq T \\ 1 & \text{if} \quad f(n) < T \end{cases} \qquad (2)$$

For k=0, 1, 2, …, K-1, where $H_f(k)$ is the number of pixels which have value k. This function has the property that:

$$\sum_{k=0}^{k-1} p_f(k) = 1 \qquad (3)$$

In histogram equalization the aim is to flat the histogram of the image i.e. make the $p_f(k)$ as a constant function. In this research, we primarily measured septum wall thickness in basal segment by use of presented computer program. Fig. 1(b) shows the intensity profile acquired from right to left ventricle in basal segment of interventricular septum. For examining this method, the intensity profiles were acquired in sequential 2D echocardiographic image frames throughout the cardiac cycles. Since there were significant intensity changes in septum edges, we thus used the thresholding technique for determining area of edges.
The pixels between two edges of septum were then counted and multiplied in pixel size for thickness calculation. In our images, the size of 0.4 mm was obtained for each pixel. Because the pixels values and contrast updates in different frames, we defined an adaptive threshold based on mean intensity value of left and right ventricular cavity and mean intensity value of the mid portion of septum wall in each segment. Adaptive threshold selects an individual threshold for each pixel based on the range of intensity values in its local neighborhood of the resulted intensity profile. We have visually evaluated threshold function using graphical stems and also superimposing used portion of line profile on images (Fig. 2a and b).

For increasing measurement accuracy, we

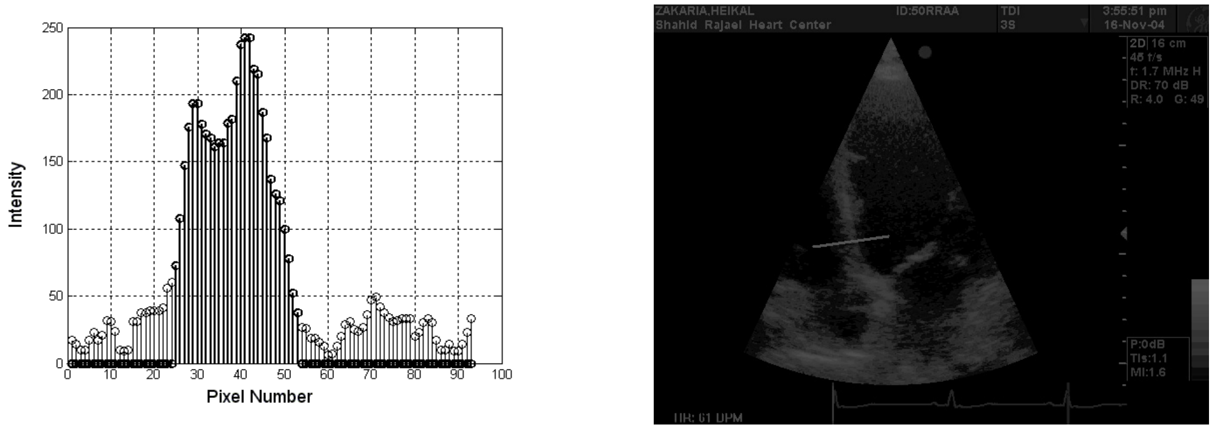

Figure 2. (a): Visual evaluation of threshold by use of graphical stems (thick stems show the use of pixels for thickness measurement) and (b): Superimposing used portion of the line profile on images (the black line which is indicated by white arrow).

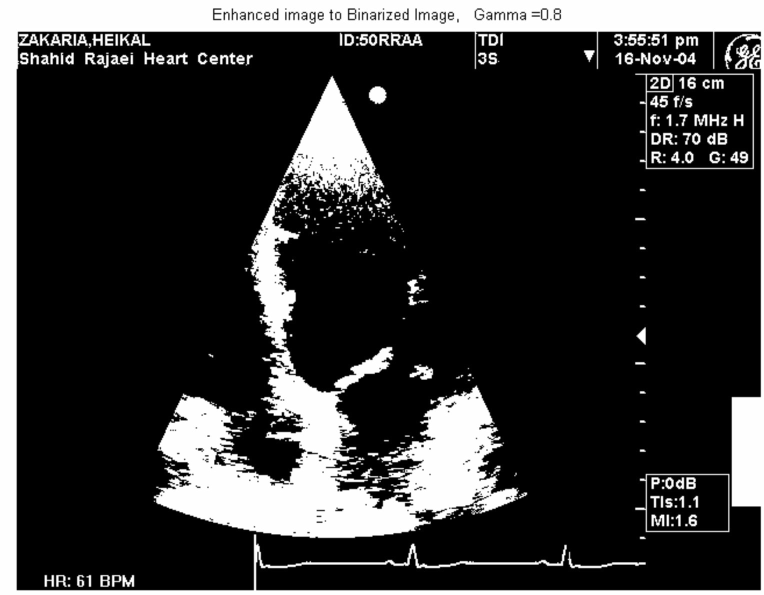

Figure 3. 2D Echocardiography image converted to a binary image

used additional parallel intensity profiles automatically as well as central profile (above and below the central profile) at intervals of one pixel to each other. In our computer program, number of line profiles is arbitrary; however in each segment, we used 3 profiles for the thickness measurement. The mean and total mean of each measurement were automatically reported.

By proposed method, thickness measurements of the septum base and mid were examined on some of acquired images throughout the cardiac cycle and compared with the results of CMM. The results show that thickness measurement error in middle segment was very high and it is worthy of mention, that we sometimes encountered an important problem due to gross changes of pixels value along septum wall (Fig1.b) because of image noise and non-uniform intensity of the septum wall. In regard to the above mentioned problems, we improved presented algorithm via converting the gray scale images to binary images by use of image processing toolbox of Matlab software (Fig. 3).

However the septum edges in binary images appeared better than gray scale images, but because of using conventional measurements, the results were underestimated, due to abstraction of information. The binary images for thickness measurement were not suitable because thickness data were loose and residual data were related to middle portion of the septum wall. But by this characteristic, we did not need using threshold process along intensity profile in the middle of each segment with subsequent reduction of random intensity changes. We used it as an advantage for determining primary septum edges with standard threshold function of image processing toolbox.

We needed to find the missing pixels belonging to septum thickness and add them to primary determined thickness. At first, for reduction of noise effect, intensity profile values were smoothed by use of a moving average filter; as the name implies, the moving average filter operates by averaging a number of points from the input intensity profile to produce each point in the output intensity profile. This is shown by the following equation:[22, 23]

$$g(n) = \begin{cases} 0 \text{ if } & f(n) \geq T \\ 1 \text{ if } & f(n) < T \end{cases} \quad (4)$$

where $H_f(k)$ and k are the input and the output profiles respectively. *M* is the number of points used in the moving average. By comparing mean values with threshold, we could determine pixels that belonged to septum wall thickness. Whenever means (for example assume that mean is resulted from 5 pixels) were higher than threshold level, the first pixel are added to septum thickness and then means of second 5 pixels were compared with threshold level, if it was lower than threshold level. This means that residual pixels did not belong to septum thickness. Finally, we counted all computed septum pixels in each segment and multiplied it by image pixels size (0.4mm in our study). The above mentioned method could semi-automatically measure accurate thickness in horizontal direction of intensity profile in sequential multiframe. For thickness measurement in oblique direction, we found coordination of pixels that were at the beginning and the end of the used intensity profile with equivalent distance calculated in terms of pixel automatically based on pythagoras equation.

Statistical Analysis

All measured values were analyzed using SPSS13 (SPSS Inc. Chicago, IL, USA). In this study twelve healthy males were included after having submitted the written informed consent. All participants had a normal ECG, normal visual function in echocardiogram, and no history of heart disease, angina, hypertension or diabetes. Their resting heart rates varied between 60 to 88 beat per minute (mean 72±9 bpm). The study protocol was approved by the ethics committee of Tarbiat Modares University. We selected ten image frames of each healthy volunteer in random order (total 120 frames and 240 segments). Two measurements were taken with each method on the same segments of the image frames. Only the first measurement was used to illustrate the comparison of the methods, the second measurement was used for reproducibility. Pearson coefficients of correlation and limits of agreement (LOA) were calculated for comparisons of the septum wall thickness regarding the CAM and CMM. Intraobserver variability for each method was defined as differences between measurements expressed as a percentage error of the means.

Results

To investigate validity and applicability of the proposed semi-automatic wall thickness analysis in 2D echocardiography images, the CAM and CMM were used on the same 120 image frames in the same segments and Pearson correlation analysis was applied for comparisons of the results between two methods. Pearson correlation coefficients were 0.87 (P<0.001) and 0.89 (P<0.001) for thickness of the septum base and mid, respectively. There were significant correlations between the measurements at each segment (Fig. 4).

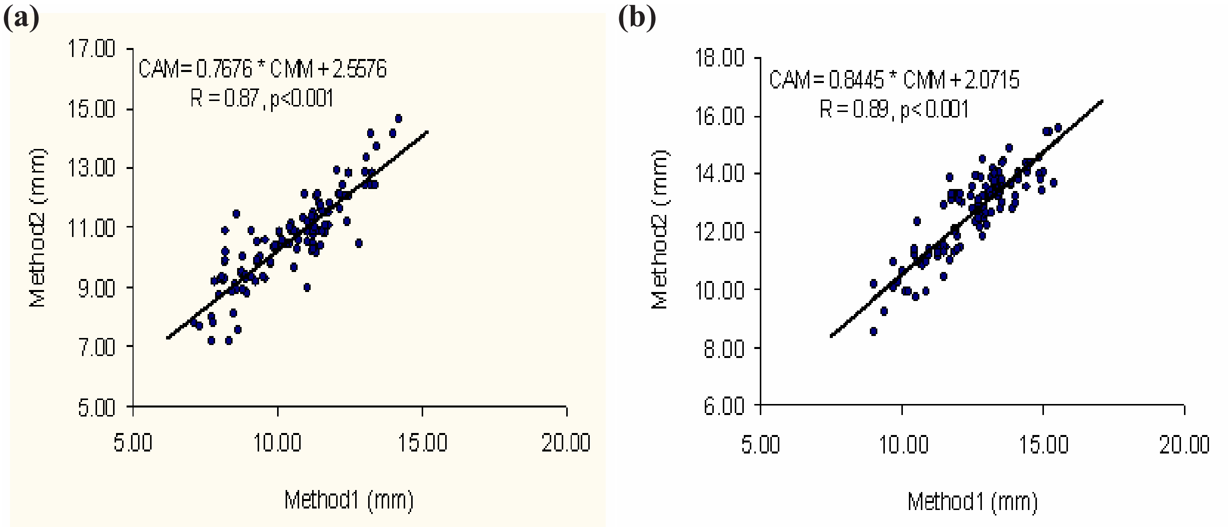

Figure 4. Correlation between the computer assisted method (CAM) and conventional manual method (CMM) in (a) septum base and (b) mid segments.

As the use of correlation alone may be misleading, an additional procedure which was a scatter plot of the difference between measurements against the mean of the measurements was then constructed. This was based on the technique described by Bland and Altman (1986)[24] for assessing agreement between two methods of clinical measurement with 95% LOA (mean difference ± 2SD).

According to this analysis, mean differences were 0.10mm (SD=0.81) and 0.12mm (SD=0.72) for basal and middle segments, respectively (Fig. 5).

Interobserver variability for septum base and mid was found to be 4.0% and 2.4% for CAM and 4.6% and 3.9% for CMM respectively. Both values of CAM are lesser than CMM for thickness of septum base and mid segments.

Discussion

The 2D echocardiography images have poor signal to noise characteristics and low spatial resolutions. Numerous attempts have been made to develop different algorithms for quantitative analysis in these images in order to measure heart wall thickness, but as yet

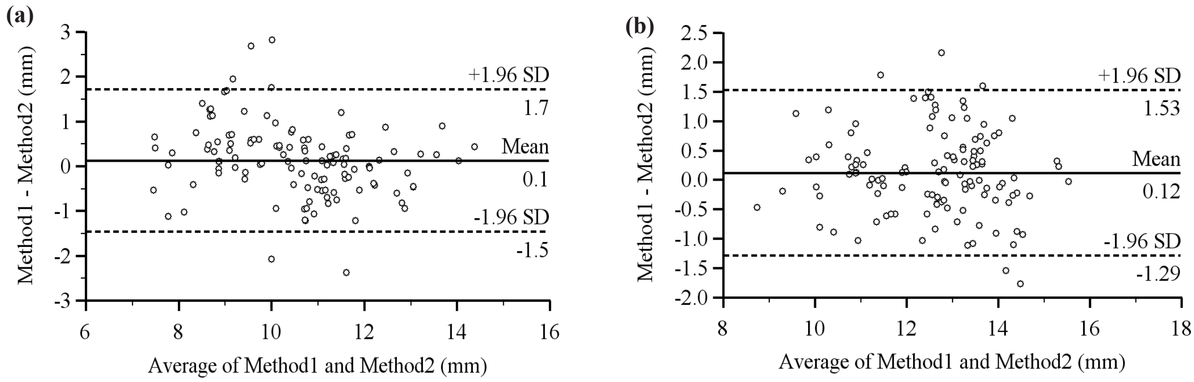

Figure 5. Bland and Altman graph with the LOA for septum wall thickness measurements (mm) at the base (a) and mid segments (b) for 120 image frames separately (Method1 and Method2 are computer-assisted and conventional manual measurement methods respectively)

none have been adequately developed. As previously stated, we have briefly surveyed some advances in the fields of echocardiographic image processing and some of their characteristics and problems are discussed herein. The results indicated that Sobel and Laplacian operators usually produced a large number of false responses as missing changes vary less abruptly and detecting significant features has been more important when information derived from any stop frame in an image sequence is severely affected by noise.[25] The optical flow approach has some advantages in that border recognition algorithms are no longer needed.[26] Unfortunately these methods have problems which hinder their clinical usage. Optical flow methods are well known for being sensitive to image noise. As optical flow tracking refers to the computation of the displacement field of objects in an image, the assumption of intensity conservation is typically unrealistic for medical imaging applications.

Snakes are also unlikely to work well on low-quality images where noisy feature measurements will tend to make them wander into noisy areas of the image. Also there is a distinct possibility that different human operators would produce different results on the same data, through slightly different initializations.[26]

Our objective was to prove that simple and effective method may also achieve the goal. The present study presented one approach for simultaneous extraction of the regional septum boundaries for thickness measurement from 2D apical four-chamber echocardiographic images and compared their performance with the CMM. The accuracy of the thickness measurement in poor quality images may need improving. The program can reliably estimate septum wall thickness in base and mid segments in our echo images and myocardial boundary recognition in desired wall segment is adaptive and autonomous and human input need only initial estimation of the segments location. For this reason, since the boundary features cannot be extracted by simple gray level threshold in most wall segments, due to image noise and non-uniform intensity of the septum wall, therefore thickness measurement was achieved based on adaptive bilateral threshold method to delineate the left and right endocardial interfaces separately using gray scale and binary images simultaneously. We evaluated the validity of the algorithm in comparison with CMM in the same image frames and approximately similar results were observed for two methods. Finally, this was applied to the regional thickness analysis of the septum. In this study, close agreement was observed between the paired thickness measurements: The Bland-Altman analysis revealed a good concurrence between the used methods, because 95% of differences lay between the mean plus and minus 1.96 SD (Fig.5). Line of equality or identity on the scatter plots indicated that the thickness values measured by CAM in basal segment slightly underestimated the values measured manually in diastolic phase of the cardiac cycle which seemed mean intensity value decreases and threshold function did not act as well as systolic phase (Fig. 6).

The mean differences in thickness values obtained by the methods were small and were not statistically significant. There was a good correlation between methods. Also the comparison between the results showed that thickness

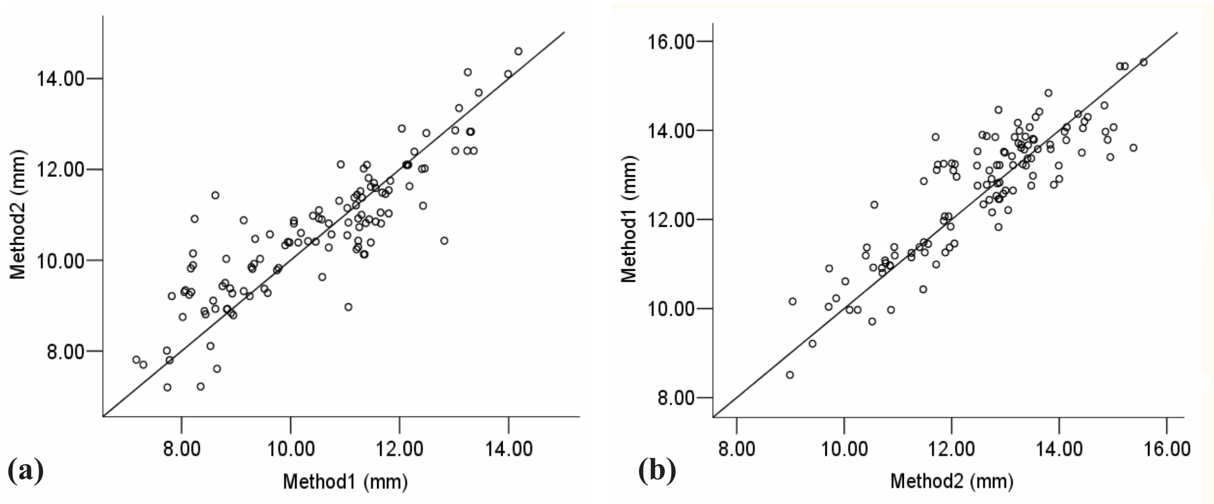

Figure 6. Line of equality (a) for the septum base and (b) mid segments separately for 120 image frames (Method 1 and Method 2 are computer-assisted and conventional manual measurement methods respectively).

measurement determined by the presented method produced accurate results after smoothing of the intensity profiles.

The results confirm that computer-assisted semi-automatic measurement of wall thickness is applicable to 2D echocardiographic images and has potential for measuring these images.

The method presented in this study is used only for septum base and mid wall segments in healthy persons and to explore applicability and potential of the proposed method to other left ventricular wall segments in normal individuals and patients using 2D echocardiographic images are the subjects of our future investigation.

Acknowledgements

This work was financially supported by Vice Chancellor for Research of *Tarbiat Modares University* University of Medical Sciences. The authors declare that they have no Conflicts of Interest.

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