IMPROVING MYOCARDIAL CONTRAST ECHOCARDIOGRAPHY (MCE) IMAGES REGISTRATION BY INCREASING IMAGES SIMILARITY

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Abstract

MCE is starting to be introduced into clinical practice. For quantitative assessment of myocardium perfusion and coronary artery disease, MCE protocols depend on a reasonable alignment of the images or ROIs. Therefore, automatic registration may increase the accuracy and also make quantification less time consuming by automating the process, what can drive a widespread clinical acceptance of this technique.

We report a first unsuccessful attempt for automatic registration of MCE sequences using a hybrid technique and describe a more reliable and efficient voxel property based approach able to register, in the average time of 15 seconds, MCE sequences of average values: 20 frames, 80 pixels of total translational and 14 degrees of total rotational offsets.

Introduction

Current ultrasound machines now offer specific facilities for MCE studies. As a result this technique is starting to be introduced into clinical practice. MCE allows qualitative and quantitative noninvasive assessment of myocardium perfusion and coronary artery disease, but usually only qualitative reading is used to interpret clinical MCE data, and its potential for quantitative analysis is almost not explored.

Protocols for quantitative studies, like Intermittent Ultraharmonic Imaging (IUH) and Real Time Perfusion Imaging (RTPI), are based on the capture of images for some cardiac cycles after the destruction of the microbubble contrast agent by a high energy pulse, followed by a fitting of a 1-exponential curve over the contrast agent replenishment data. Resultant parameters give quantitative information about myocardial blood flow and volume [1][2]. IUH and RTPI differ in the capture of images (ECG-triggered or continuously), but both use ECG-gated images for quantification. The measurement of contrast agent replenishment is performed for a ROI or pixel to pixel over the myocardium area, for each ECG-gated frame [1]. Some research has been done to develop quantitative analysis systems for MCE image sequences [3][4], and recently a commercial software became available. However, despite most of these systems are semiautomatic, they are still time consuming, which makes difficult a widespread clinical acceptance. As quantification depends on the alignment of images or ROIs, automatic registration of frames might increase the accuracy and also contribute to automate the whole process, which could make quantification less time consuming and drive a widespread clinical acceptance [5].

Despite efforts of sonographers to avoid capture of misaligned images, orientation offsets (translation and rotation) are very commom in MCE sequences due to subtle changes in transducer orientation over time, heart motion and respiratory effects. Considering sometimes it is difficult for the patient to hold the breath during a stress study, or even for the sonographer to re-acquire sequences because of some few poor (oriented) frames, translational offsets up to fifteen pixels and rotational offsets up to ten degrees or more can be found for clinical MCE data. Therefore, we believe that a registration algorithm for quantitative analysis systems of MCE images should be semiautomatic but fast enough to allow a future system inclusion in real-time scanners, and, besides accurate, robust to deal with higher orientation offsets and even changes in illumination (contrast agent rise).

Following classification presented by Maintz and Viergever [6], intrinsic registration methods can be landmark, segmentation or voxel property based, among which the two later are reliable for MCE images. Previous works [3][4] are typically cross-correlation based (voxel property-based) and were developed to correct translational motion in short-axis MCE research studies (canine models). However, clinical data is typically apical long axes view, for which besides translation, global rotation and also local deformation are present. Despite successful for such previous applications, standard cross-correlation is unable to correct for rotational offsets and is computationally heavy. On the other hand, the normalized correlation coefficient (NCC) is considered a robust similarity measure for noisy images, and recently some authors have used successfully such estimator for non-rigid registration of MCE [5] and 3-D free-hand [7] ultrasound images.

Our first attempt to register MCE images was using a hybrid technique (segmentation and voxel property based) to improve images similarity and make easier the registration. We first segmented the left ventricle (LV) in each frame using an active contour (LV contour drawn by the user on a reference image) propagated frame to frame after LV borders matching. Next we changed the intensity value of all pixels inside the segmented region (LV) of each frame to a maximun intensity (white). And finally all modified frames were cropped (from borders to center) to get half the size of its original dimensions, and a cross-correlation between the reference and each frame, both sub-sampled, was performed to evaluate the translational motion. The high definition of endocardium borders due to contrast agent inside the LV made suitable the automatic segmentation, and the common modified regions (LV) in each frame did improve the similarity between images, making the process more robust for contrast rise. However, after apparently good results in initial tests with not so poor sequences, we found problems when testing poor oriented images. For sequences with frames of high orientation offsets, the active contour propagated from the previous frame was not able to deform and track adequately the LV borders of a next high displaced image, compromising the segmentation of the following frames. Moreover, the segmentation was relatively slow considering that it would be still necessary to correct images for rotational motions. Another problem is the sub-sampling of unaligned images that frequently cuts off important texture information (like pieces of the myocardium) decreasing the accuracy of the cross-correlation. Due to such problems mainly related to the segmentation process, we decided to discard the hybrid approach and try a simple voxel-property based approach which fulfils our requirements of accuracy, robustness, speed of processing and semiautomatic execution.

In the next sections we describe an algorithm for global rigid registration (translation and rotation) of MCE images based on template matching and which uses a modified three-step search plus NCC for translational motion correction and an exhaustive serch plus NCC for rotational correction.

Methods

The algorithm can be divided in three consecutive phases: 1) template selection; 2) translational motion correction; and 3) rotational motion correction. Identification of both translational and rotational offsets is performed using a fixed reference image (template), and the precision of the algorithm is one pixel for translation and one degree for rotation.

1) Template selection

Before selecting the template it is necessary to choose which frame of the ECG-gated sequence will be used as reference for registration. The average image of all original frames is determined and the NCC between this image and each frame calculated, and the frame of best NCC is the reference image.

After selection of the reference image, the user interactively draws a closed polygonal contour of the myocardium (Figure 1) over this image. The smallest rectangle that fits in the drawn myocardium region determines the template for registration (Figure 1).

Figure 1: The reference template and the drawn myocardium contour (not part of the template image).

2) Translational motion correction

The cross-correlation between the template and the image to be aligned is for sure the optimal estimation of global translational offsets, however is computationally heavy and consequently slow. A similar problem happens in real time video encoding (e.g. MPEG) when a block matching algorithm is used to estimate the motion of moving pictures for data compression. The best estimation is taken with a full search of each small block (template) over the search window in the subsequent frame, but like cross-correlation for image registration, it is too slow for such purpose. The solution for such cases is to use fast motion estimation algorithms, being the Three-Step Search (TSS) (Figure 2) the most popular due to its simplicity, regularity, reasonable performance and significant computational reduction (~90%) [8].

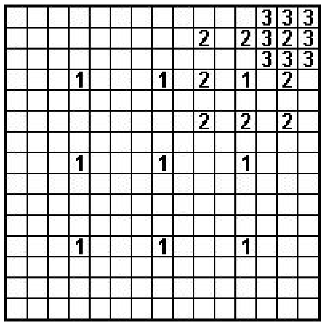

Figure 2: Illustration of the three-step search.

For translation estimation, to overcome the speed problem of the cross-correlation without discarding the robustness of the NCC as the similarity estimator, we use a modified TSS to search for the point of best correlation between the template and the image under correction. The first and third search steps are identical to original TSS, but the second step runs iteratively until the matched point is located in the center of the search window. This makes possible the estimation of any value of translational offset within the image limits, beyond the limit of 7 pixels of the original TSS. With this modification the elapsed time for searching becomes proportional to the magnitude of the offset. The higher the offset, the slower the processing. Basically, the first step determines the direction of the displacement, the second step is a gross estimation of the offset, and the third step refines the estimation with a resolution of one pixel. This search strategy is executed for each frame of the sequence and the found translational offsets are corrected for by translation of the original images.

3) Rotational motion correction

As mentioned in the Introduction, the standard cross-correlation and consequently the template matching technique are unable to deal with rotational offsets, unless different templates obtained from a range of rotational angles applyed to the original template are used, which can be computationally heavy depending on the expected range of rotation offsets and on the implementation of the algorithm.

For rotation estimation we perform an exhaustive search with rotated templates, however we use specific strategies to reduce the computational cost of the algorithm based on the following assumptions: 1) after previous translation correction the spatial location of the myocardium region on each pre-aligned image is the same as in the reference image. This means that each pre-aligned image can be sub-sampled with low loss of texture information using the coordinates of the rectangle which specifies the template in the reference image; and 2) the NCC value is maximun when template and image are oriented in a same rotation angle, and decreases while the rotational offset between images increases.

In the first step, the "direction" of rotation (clockwise or counterclockwise) of each frame is identified. The NCC between the template and a sub-sampled rectangular image of each frame is calculated for the original template (NCCO) and also for the template rotated one degree clockwise (NCCR) and one degree counterclockwise (NCCL). Comparing these three values obtained for each frame, the direction of rotation of each frame is identified as showed below.

NCCO ≥ NCCL and NCCO ≥ NCCR => no rotation
NCCO < NCCL => counterclockwise ('left') rotation
NCCO < NCCR => clockwise ('right') rotation

The second step is iterative and runs until the rotational offset is identified for each frame. After determination of the directions of rotation (previous step), if any frame of the sequence has, for example, a clockwise rotation (NCCO<NCCR) identified, the template is rotated one degree more to 'right' and the NCC between the new rotated template and the sub-sampled frame is calculated again (NCCnew). If NCCnew ≤ NCCold (NCC for the previous angle of template rotation) the absolute rotational offset of the frame is considered equal to the current template angle minus 1. Otherwise, the search continues until the condition NCCnew ≤ NCCold is matched. This same procedure is executed for the counterclockwise rotated frames and the algorithm iterates until the condition NCCnew ≤ NCCold is matched for all frames and all rotational offsets are identified.

It is important to note that everytime the template is rotated, for example, clockwise, the NCC comparison is done for all sequence frames which have clockwise rotation identified. Also, the rotation angle of the template is incremented only one degree per iteration, and when the condition NCCnew ≤ NCCold is matched for a frame, this frame is not tested anymore in the following iterations. This statement is also valid for counterclockwise rotation. Moreover, in each iteration clockwise and counterclockwise rotational offsets are searched simultaneously.

For rotation of the template and also for correction of the determined offsets of each frame, we use Nearest Interpolation to render the rotated images.

Results

The algorithm was implemented in the Matlab software and tested in a 847MHz / 256MB RAM personal computer. All processing was performed in the spatial domain with grayscale images (256 shades) of original size 320 by 222 pixels (width x height).

Figure 3 shows the registration of a poor oriented image (B) 11 pixels right translated and 10 degrees counterclockwise rotated. Black arrows in B and C point the global translation correction, and white arrows in C and D the rotation correction. Comparison of A and D confirms the accuracy of registration.

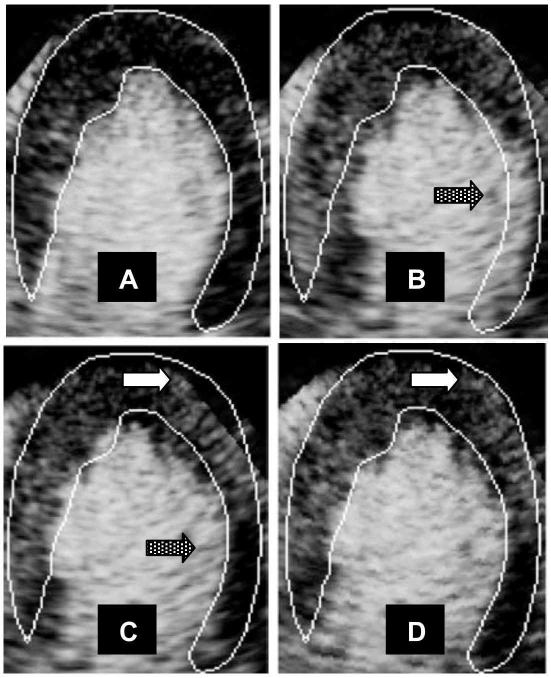

Figure 3: A) reference; B) original image; C) translation corrected; D) transl.+rotation corrected.

A qualitative test was performed by an experienced MCE researcher. The protocol consisted of a visual comparison of both original and registered sequence movies and also a close comparison of each registered frame and the reference (Figure 3). After analysis, sequences were classified as 'Best' (all frames well aligned), 'Good' (acceptable if few bad aligned frames are discarded) or 'Poor' (poor alignment, unacceptable for quantification). Sixteen ECG-gated sequences (314 images) were used for testing, 2 IUH and 14 RTPI, and the result is showed in Table 1. Table 2 presents statistic about the processed data of all 16 sequences, for which 'total time of processing' = (RGB/Gray image conversion + template selection + registration + creation of movies and figures) times.

Table 1: Result of registration test.

Classification of the registered sequence	Number of sequences	Percentage of the total
BEST	13	81%
GOOD	3	19%
POOR	0	0%

Table 2: Statistical results of the processed data.

Values / sequence	Min.	Max.	Aver.	Std. Dv.
number of frames	11	29	19.6	5.2
max. transl. (pixels)	3	15	7.8	3.5
max. rotat. (pixels)	1	10	2.8	2.1
total transl. (pixels)	18	149	79.9	40.2
total rotat. (pixels)	1	53	13.8	12.3
time for transl. reg.	3.8s	12.0s	8.2s	2.6s
time for rotat. reg.	2.3s	15.0s	6.8s	3.2s
time for registration	6.7s	26.7s	15.0s	5.5s
total time of proc.	56.3s	99.3s	79.6s	13.1s

Discussion

The 3 GOOD sequences had one frame discarded each one, all comprised either in the sequence beginning or end. These frames had some translational and rotational offsets corrected, but were discarded by precaution due to some remaining misalignment.

From Table 2, the high standard deviation of 'total translational' and 'total rotational' offsets corrected per sequence, and also de huge difference between the minimum and maximum values found within all sequences, prove the diversity of the tested samples. Second, the average values of these same indicators confirm that translational offsets (79.9 pixels) are much more commom in MCE images than rotational (13.8 degrees), as expected. Third, despite the average time for translation and rotation registration are similar (8.2s and 6.8s), considering the average values of total translational (79.9 pixels) and rotational (13.8 degrees) offsets corrected per sequence, we confirm as expected that the modified TSS used for translation motion correction is computational more efficient than the exhaustive search used for rotation correction.

In [5] a non-rigid MCE registration algorithm was validated by a manual translational correction, which might indicate that a rigid registration is sufficient for quantitative analysis systems of MCE data. Moreover, the commercial software available at date uses only rigid manual alignment (translation) of ROIs.

Conclusions

The average time of 15s for registration of sequences of 20 frames, 80 pixels of total translation and 14 degrees of total rotations on average, indicates the algorithm is computationally efficient despite non-optimized and implemented in Matlab. Moreover, 81% of sequences perfectly aligned and 19% of sequences aligned with no significant failures make us conclude the algorithm is accurate and robust to deal with high orientation offsets and contrast agent rise.

References

[1] K. Wei, A.R. Jayaweera, S. Firoozan, A. Linka, D.M. Skyba and S. Kaul, "Quantification of myocardial blood flow with ultrasound-induced destruction of microbubbles administered as a constant venous infusion", Circulation, vol. 97, pp. 473-483, 1998.

[2] K. Wei, M. Ragosta, J. Thorpe, M. Coggins, S. Moos and S. Kaul, "Noinvasive quantification of coronary blood flow reserve in humans using myocardial contrast echocardiography", Circulation, vol. 103, pp. 2560-2565, 2001.

[3] A. Linka, J. Sklenar, K. Wei, A.R. Jayaweera, D.M. Skyba and S. Kaul, "Assessment of transmural distribution of myocardial perfusion with contrast echocardiography", Circulation, vol. 98, pp. 1912-1920, 1998.

[4] A.R. Jayaweera, J. Sklenar and S. Kaul, "Quantification of images obtained during myocardial contrast echocardiography", Echocardiography, vol. 11, pp. 385-396, 1994.

[5] J.A. Noble, D. Dawson, J. Lindner, J. Sklenar and S. Kaul, "Automated, non-rigid alignment of clinical myocardial contrast echocardiography image sequences: comparison with manual alignment", Ultrasound in Med. and Biol., vol. 28(1), pp. 115-123, 2002.

[6] J.B.A. Maintz and M.A. Viergever, "A survey of medical image registration", Medical Image Analysis, vol. 2(1), pp. 1-36, 1998.

[7] G. Xiao, J.M. Brady and J.A. Noble, "Nonrigid registration of 3-D free-hand ultrasound images of the breast", IEEE Transactions on Medical Imaging, vol. 21(4), pp. 405-412, 2002.

[8] J.-N. Kim and T.-S. Choi, "A fast three-step search algorithm with minimun checking points using unimodal error surface assumption", IEEE Transactions on Consumer Eletronics, vol. 44(3), pp. 638-648, 1998.

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