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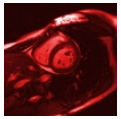
Use of Motion Field Warping to Generate Cardiac Images

by ***Gang Gao*** and ***Paul Cockshott***

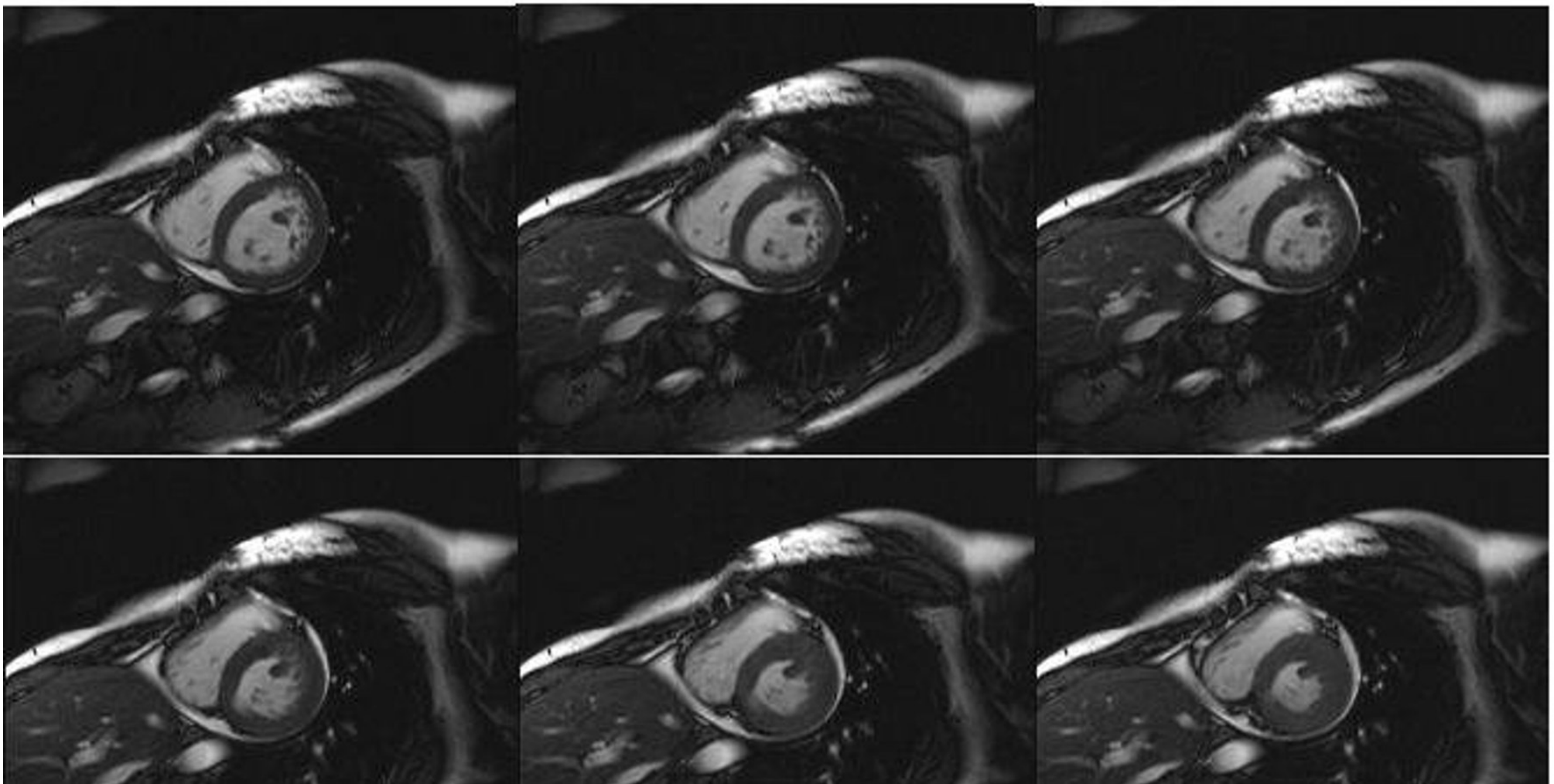


Abstract

In this study, we developed an algorithmic method to analyze late contrast-enhanced (CE) magnetic resonance (MR) images, revealing the so-called hibernating myocardium. The algorithm is based on an efficient and robust image registration algorithm. Using our method, we are able to integrate the static late CE MR image with its corresponding cardiac cine MR images, constructing cardiac motion CE MR images, which are referred to as cardiac cine CE MR images. This method appears promising as an improved cardiac viability assessment tool.

Introduction

Acute myocardial infarction (MI) is commonly known as a heart attack. It occurs when the blood supply to a part of the heart is interrupted. Cardiac MR imaging is an increasingly important MI diagnostic tool. When a patient has suffered a heart attack, the surgeon needs to know whether the patient would benefit from coronary bypass surgery. For the surgery to be effective, there must exist heart muscle that, while stunned by the attack, is still alive, and thus capable of regeneration if given improved blood circulation.



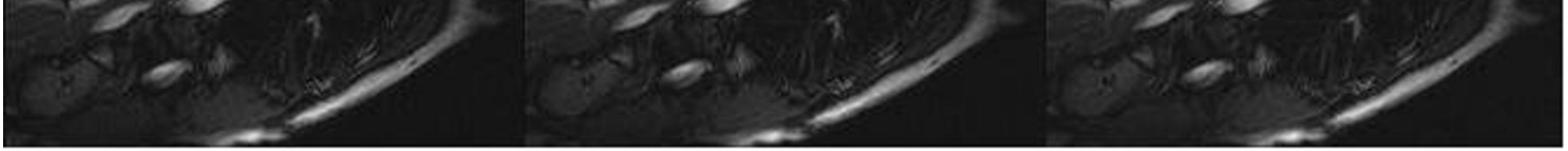


Figure 1. A cross-sectional cardiac cine MR sequence reveals the anatomical structure as well as the motion of myocardium. The existence of cardiac disease can be detected preliminarily by the observation of cardiac motion.

MR imaging is a unique tool for the clinician to view the activity and viability of the living heart. For this purpose, it is classically used in two modes, referred to respectively as cine and late enhancement imaging. As its name suggests, cine MR provides a moving picture of the beating heart, as can be seen in Figure 1. It relies on the formation of many frames of MR images being captured during the course of each cardiac cycle. This provides the surgeon or radiologist with indications as to whether or not the heart is pumping normally, and it allows one to measure the volume of blood that is being shifted with each cycle. This will reveal any abnormalities, but it gives the doctor insufficient information to decide whether proceeding with surgery is the best course.

If an area of the myocardium is observed to have abnormal motion, cine MR cannot tell us whether this is because the tissue is effectively dead or because it is stunned and might improve after surgery. In order to make this determination, late enhancement or contrast-enhanced MR is used. This involves injecting patients with gadolinium-diethylenetriamine pentaacetic acid (Gd-DTPA) [**4**,**5**,**8**]. A slower speed MR scan performed following such an injection will show dead tissue as a lighter shade on the image. These lighter regions are termed "late contrast-enhanced" (Figure 2).

CE MR has become a widespread and effective technique to visualize and quantify myocardial infarction. Myocardial viability is assessed by visual evaluation of wall motion abnormalities in combination with the presence or absence of late enhancement. Myocardial regions without late enhancement but with contractile dysfunction are considered as injured but viable. The dysfunctional, yet viable, myocardium is often referred to as hibernating myocardium.

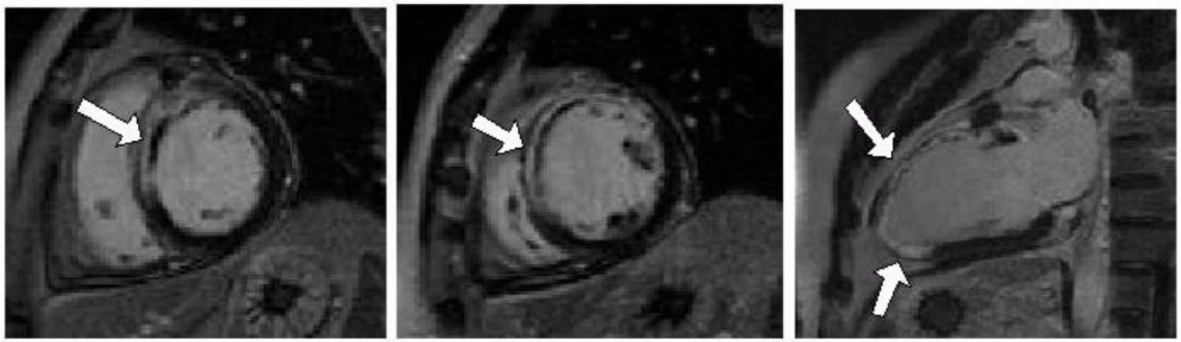


Figure 2. After the injection of Gd-DTPA, a slower speed MR scan shows MI as a lighter shade on the image. MI can therefore be assessed by the measurement of the lighter area in myocardium.

At present, cardiac cinematography MR images and CE MR images are acquired separately [**1**] and then compared to each other to identify hibernating myocardium. The fact that two different imaging techniques are being used can lead to difficulties in assessment. The clinician has to switch visual attention between two images: a moving cine image and a still CE image. This division of the viewer's attention is aggravated in situations where patient motion and respiratory motion are present. The result can be diagnostic errors. To address this issue, research is underway to produce a cine MRI with contrast enhancement. However, no satisfactory results have been reported so far.

Chen and his colleagues acquired cine MR images after the injection of Gd-DTPA. This method maintains good temporal resolution but sacrifices image contrast [**1**]. Ding's method produces better contrast in images, but the temporal resolution is too low to cover a cardiac cycle [**3**].

While other researchers are trying to improve the capability of MR scanners, we propose an algorithmic solution to address this problem. Our method is both novel and accurate. It utilizes an image registration technique that extracts cardiac motion from cine MR images. The motion data can subsequently be used to digitally warp the contrast-enhanced image, producing moving contrast-enhanced images. Our method overcomes previous difficulties, producing cine CE images with both satisfactory contrast and high temporal resolution. The new method requires no new equipment and allows assessments to be made on existing CE MRI images because it is a postprocessing technique.

Method

Registration

Given two images, I and J, image registration finds the transformation function T such that $I` = I(T(x, y))$, where $r = min\ \delta(I`, J)$.

The function δ is a predefined similarity measurement, with possible minima r. The metric used in our case is a cross correlation between local 5 x 5 pixel windows centered on each pixel.

The registration software used was derived from research undertaken earlier in the context of stereo vision [**2**,**4**,**6**]. In the original setting, the algorithm had been used to determine the correspondences between pixels seen by the left and right cameras of a stereo pair.

The algorithm, called MSSM, uses image pyramids. For each image of the pair *[A,B]* to be registered, a differential pyramid is constructed. The scale ratio between the layers is $^2/_3$. The topmost layer is nondifferential and is typically on the order of 20 pixels across.

The pyramids are used top down to search for corresponding regions in the two images. First, a local search is carried out to find, for the 5 x 5 region around each pixel in A_{top}, the displacement to the center of the 5 x 5 region in B_{top} that is most closely correlated to it. The local search is carried out within a one-pixel displacement radius.

Subpixel accuracy is obtained by fitting a two-dimensional parabolic surface of the cross correlation metric at integer pixel displacements and selecting a displacement corresponding to the maximum of this surface.

The displacement vectors for each pixel are then smoothed with a convolution kernel to ensure that there are no sharp discontinuities in the displacement field. This is consistent with the fact that the cardiac wall undergoes continuous rather than discontinuous deformation.

The first estimate of the displacement field is then used to warp image B_{top} to obtain B_{top1}, the best estimate of A_{top} that can be obtained by the current estimate of the warping field. The previous matching process is now repeated between A_{top} and B_{top1} to obtain a second, more precise estimate of the warping field at this level.

The warping field obtained from the topmost layer is scaled by 1.5 and then used to prewarp the second-from-top layer of the image pyramid for image B. Correlation optimization and warping are again applied at this level to obtain an improved estimate of the warping field for the second-from-top level of the pyramids.

The process then continues recursively down the pyramid until it terminates at the base with an estimate of the overall flow field.

The algorithm utilizes pyramids to accelerate the search. Pyramids allow the gross work of finding the best estimate of displacement to be achieved by local searches on the upper levels of the pyramid. Going down the pyramid, these gross estimates are refined. Figure 3 shows the motion data extracted from three slices of a cardiac cine MR scan. The objective of image registration in this study is to extract cardiac motion from the cardiac cine MRI and correct the misalignment between the cine MRI and the CE MRI.

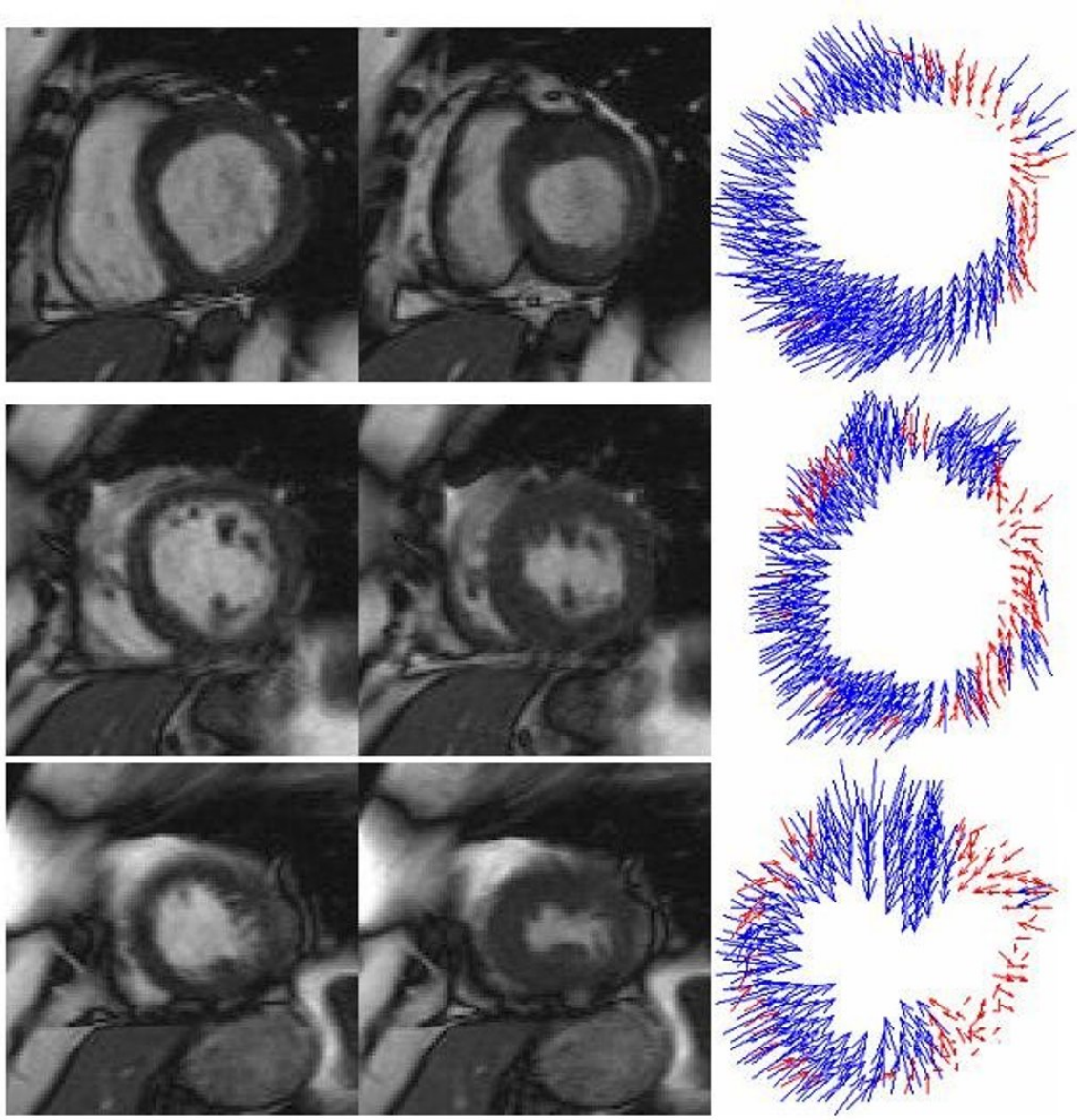


Figure 3. Cardiac MR images were acquired from the base, middle, and the apex of the myocardium. MSSM matched the end diastolic and the end systolic images, producing disparity maps. Cardiac motion was derived from the disparity maps and shown as small arrows. The direction and the length of the arrow shows the direction and distance of cardiac motion. A threshold can be manually defined (5 mm in this study) to differentiate healthy and unhealthy cardiac motion. The arrows with a length greater than the threshold are shown in blue, indicating the normal cardiac motion. Similarly, the arrows shorter than the threshold are shown in red, suggesting abnormal cardiac motion.

CE Cine Images

From a cardiac cine MR sequence, a reference image is selected manually. The selected reference image should be acquired close to the point in time within the cardiac cycle that its corresponding CE MR image is acquired from. Misalignment between the CE MR image and the reference image was corrected using a mutual-information based rigid image registration algorithm. Mutual information is a powerful similarity criterion, especially in multimodality image registration, because of its immunity to contrast variation. A global search was utilized to find the optimized transformation. Once the translation function T_{global} is determined, it is applied to the entire CE image $I`_{CE} = I_{CE}(T_{global})$, where $I_{CE}$ is the original CE MR image and $I`_{CE}$ is the motion corrected CE MR image.

The reference image is registered with other images in the cine sequence using the matching algorithm described above, building a set of disparity maps, $T_{n=1...m}$, where m is the number of images in the cine sequence. The misalignment corrected CE MR image, I_{CE} is digitally warped using the disparity maps, $I_{warped\ CE,\ n=1...m} = I_{CE}(T_{global} + T_{n=1...m})$

Experimental Results

MR Data Acquisition

MRI was performed on subjects with a median age of 69 years on a Siemens Sonata 1.5T system using a phased array chest coil. Left ventricle dimensions were evaluated using a cine TrueFISP breath-hold sequence. Cardiac triggering was used in the scan. Image parameters were repetition time of 3.2 ms, echo time of 1.58 ms, 208 x 256 matrix sizes, and flip angle of 52°.

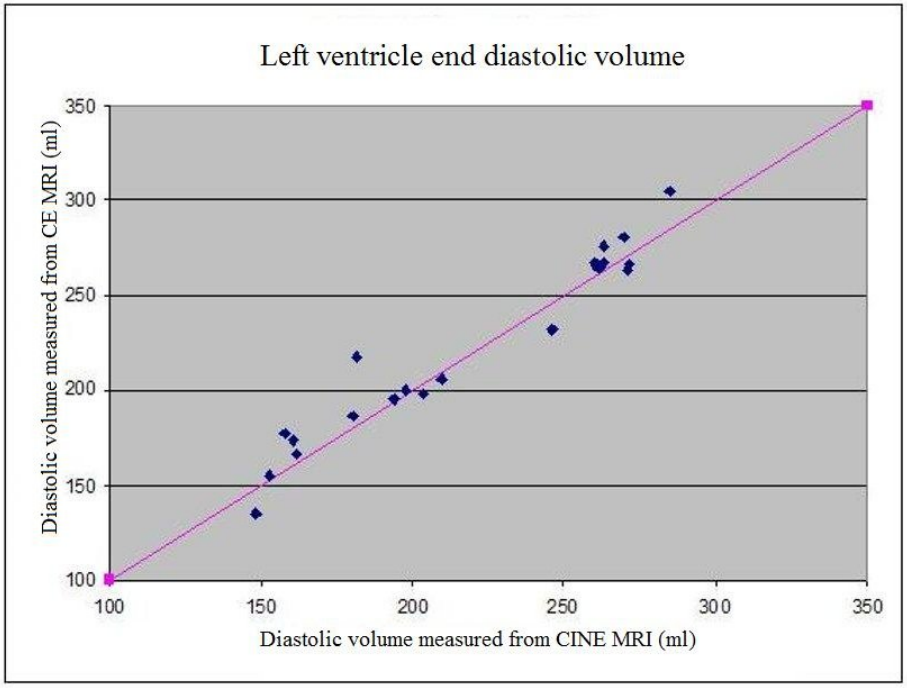
CE MR was performed 10 minutes after injection of 0.2 mmol/kg Gd-DTPA using a breath-hold segmented TurboFLASH inversion-recovery sequence. The image parameters, including the field of view, matrix size, slice thickness, and slice gap, were identical to the corresponding cine MR images.

Experimental Results

Twenty patients with chest pain who were late contrast enhancement positive were recruited. A reference image was selected manually from each of the short axis slices. The misregistration between the reference image and its corresponding late contrast-enhanced image was corrected using a mutual-information based full search registration algorithm. MSSM was employed to extract the motion fields from each of the short axis slices. The corrected contrast-enhanced MR images were warped to build the cine CE image.

The mean of the cardiac parameters, including the left ventricle end diastolic volume and left ventricle end systolic volume, were compared between the original cine sequence and the warped sequence. The Student's t-test value, p, was computed to reveal the statistically significant differences between the two data sets. The two data sets were deemed to have no significant differences if the t-test value was greater than 0.05.

Mean left ventricle (LV) diastolic volume in each of the slices was measured by planimetry (original/warped = 206/215 ml). The t-test, with $p = 0.35$, shows there is no significant difference between the left ventricle diastolic volume of the original image and the warped image. The left ventricle systolic volume (129/123 ml), had $p = 0.33$. The overall data are presented in Figure 4. Figures 5 and 6 show examples of the cine CE sequence.



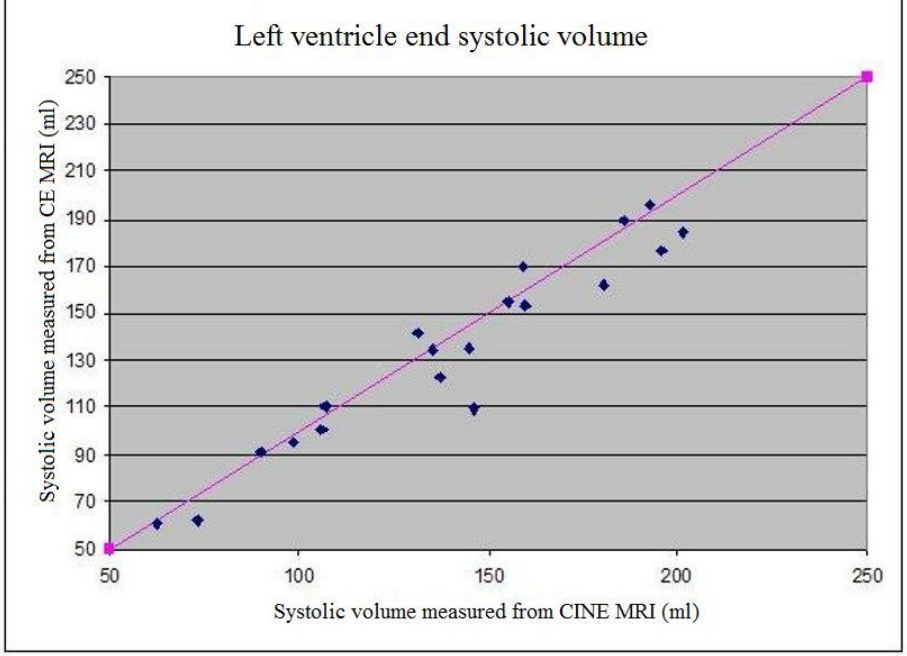
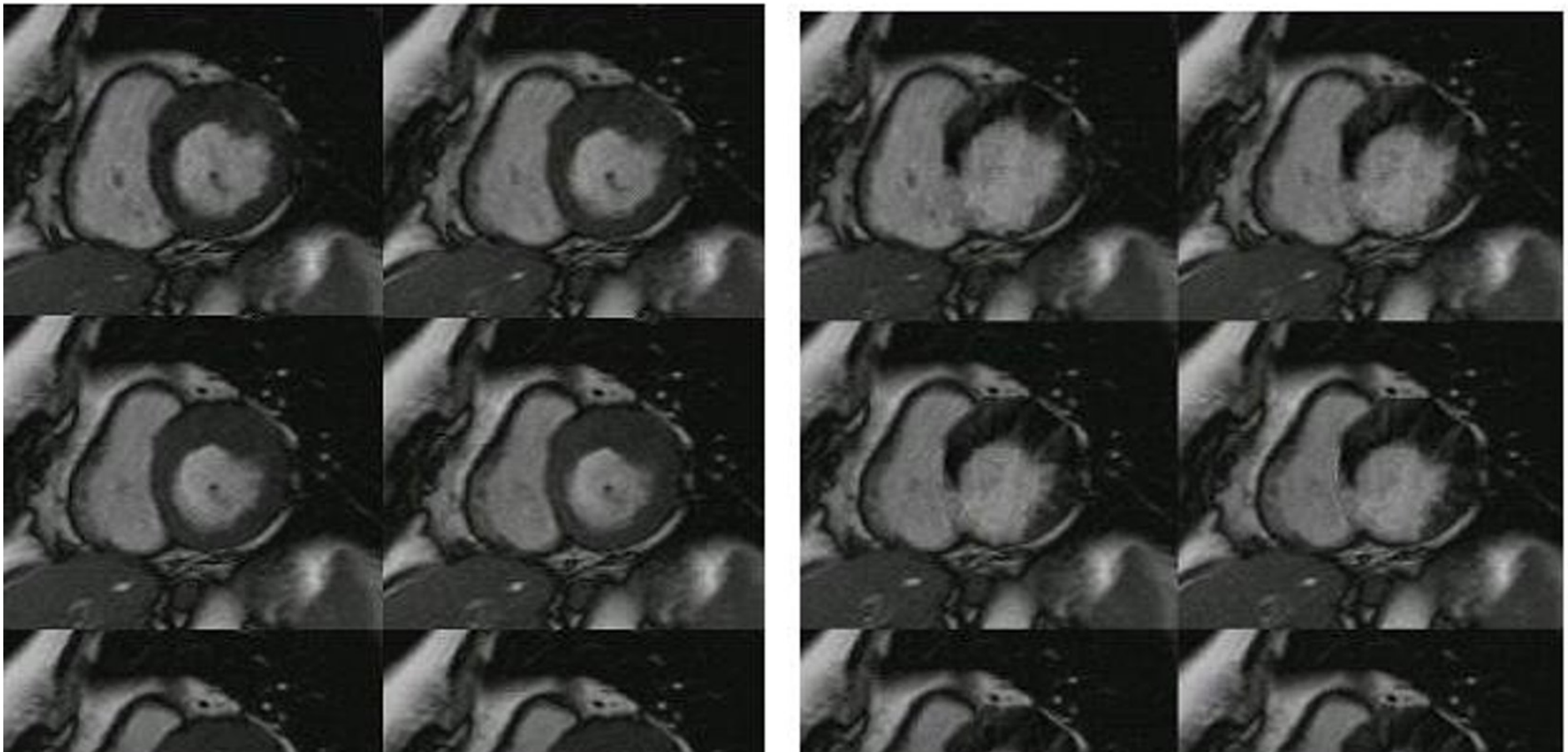


Figure 4. The comparison between the cine CE MR images and the original cine MR images.



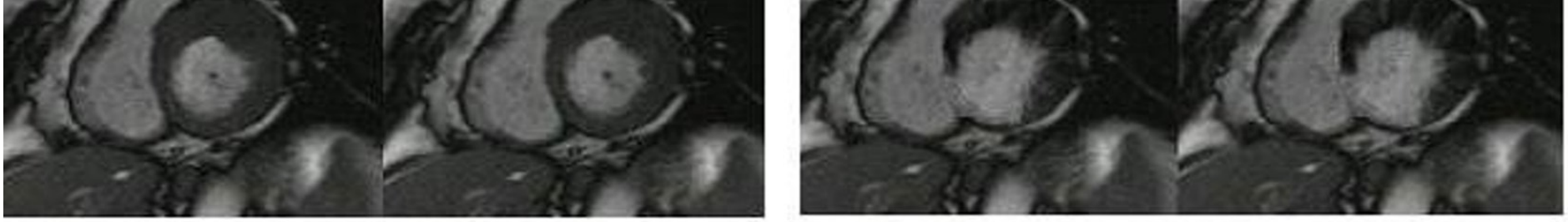


Figure 5. The cine MR images and the cine CE MR images. The six images on left are cine images. Their corresponding warped contrast-enhanced images are shown on the right.

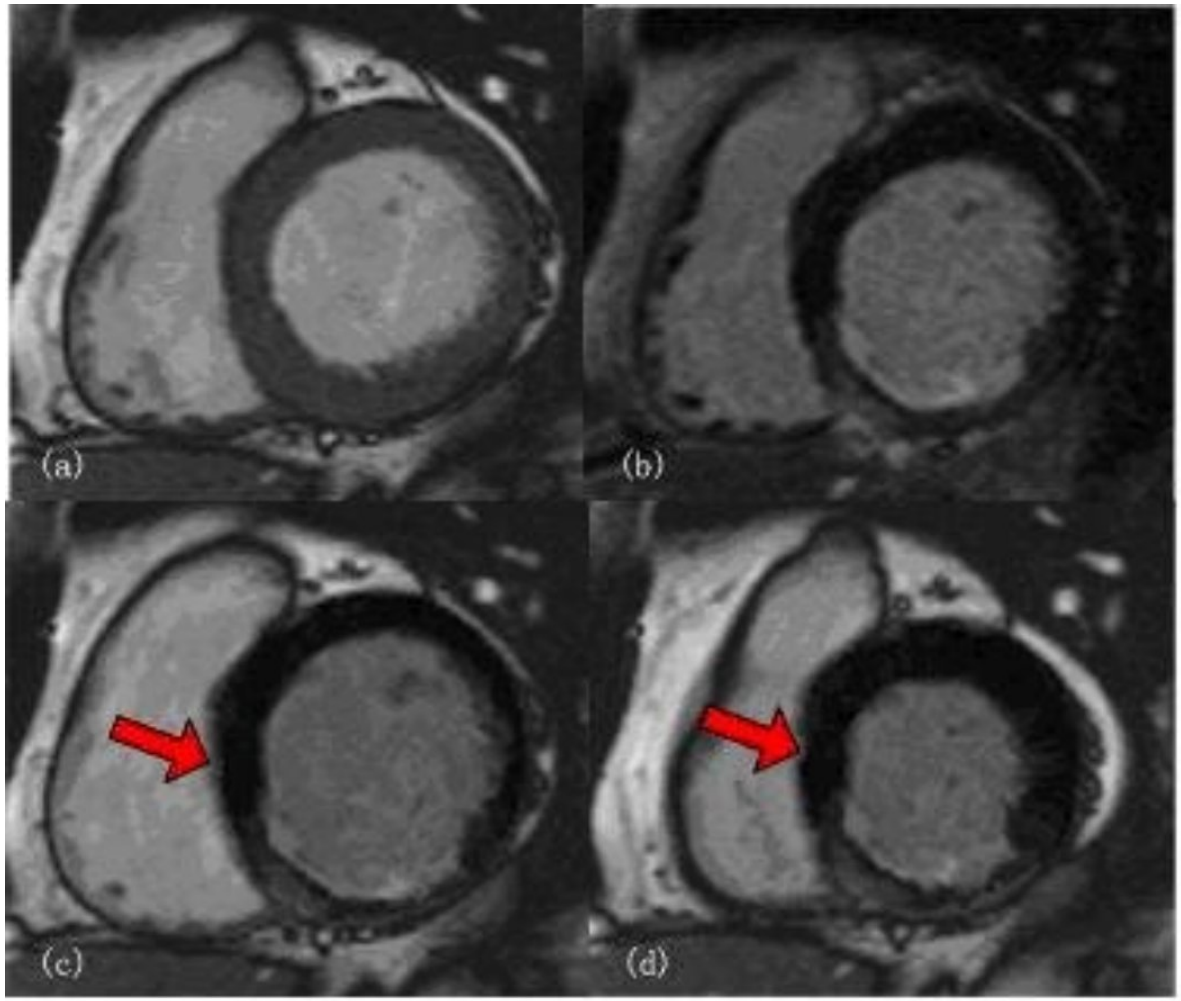


Figure 6. (a). An MR image shows myocardium at the end diastole. (b). A CE MR image shows MI as a lighter shade on the image. (c). The CE MR image was warped to the end diastole using our method. (d). The CE MR image was warped to the end systole. Cardiac motion can be revealed preliminarily by the comparison of the end diastolic image and the end systolic image. The arrow indicates the heart muscle which moves abnormally but is not contrast-enhanced, suggesting the potential hibernating myocardium.

Limitations and Future Study

The experimental results show no significant difference in LV diastolic and systolic volume between the generated CE cine MR images and their corresponding cine MR images. However, in many circumstances, errors could be produced. The image registration can only find the statistically

best estimation of cardiac motion, but the realistic motion may be different. Also, the selected reference image cannot be identical to its corresponding CE MR image.

In our study, the first error was minimized by a robust image registration algorithm which has been successfully utilized in many different areas. The second potential error source can be well controlled by use of an electrocardiographic gated MRI scanner. Vertical myocardium motion can contribute to the third potential error. Cardiac motion is complex and involves vertical motion as well as horizontal motion. Although the effect of vertical motion on the location and shape of MI is unknown, it is possible that with the presence of vertical motion, the healthy myocardium may move down or up to "replace" the MI in the 2-D slice obtained during a cardiac cycle. In other words, in the cine CE MR images, the contrast enhancement in a fixed 2-D plane may disappear gradually during the systole phase. The registration algorithm we used in this study is two-dimensional. A 2-D registration algorithm cannot predict or cope with such a situation.

A possible solution is a three-dimensional image registration. In recent years, many 3-D registration techniques have been developed. However, no report has been made about the study of cardiac cine MRI using 3-D registration. A full investigation in the future would be beneficial.

Conclusion

In this paper, a novel method for left ventricle viability assessment using combined cardiac cine and late contrast-enhanced MR images was introduced. We have shown that there are no significant differences in left ventricle diastolic volume (206/215 ml, p = 0.35) and left ventricle systolic volume (129/123 ml, p = 0.33). If we compare our method with others, ours has two clear improvements:

1. Our method is flexible as a postprocessing technique. Using our method, it is possible to produce cine late contrast-enhanced MR images from previous scans.
2. Our method integrates information from cine MRI and late contrast-enhanced MRI to produce a CE cine sequence. As a result, the output shows the best features of cine MRI images, as well as the optimum contrast and, therefore, infarct depiction of late enhancement.

Our method appears promising as an improved viability assessment tool.

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Biography

Gang Gao is a research fellow at the Centre for Medical Image Computing at University College London. He received a PhD from the Department of Computing Sciences at the University of Glasgow in 2006. His research interests include medical image analysis, registration, and calibration.

William Paul Cockshott attended McMaster University, the University of Manchester, Heriot-Watt University, and the University of Edinburgh, studying economics and computing science. His research interests include applications of computers to socialist economic planning, image coding, and physical foundations of computability.