Spatio-temporal assessment of right ventricle dyssynchronicity by magnetic resonance short-axis cine-loop segmentation

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Master thesis project

Spatio-temporal assessment of Right Ventricle dyssynchronicity by magnetic resonance short-axis cine-loop segmentation

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Abstract

This study proposes a novel method for spatio-temporal analysis of the cardiac contraction in short axis magnetic resonance imaging (MRI) cine-loops sampled at high frequency.

An algorithm capable of tracking the right ventricular (RV) endocardium during one cardiac cycle was implemented in Labview. The implemented algorithm measures the radial displacement of the endocardium along a set of rays originating in the left ventricle (LV) center. From this information, motion signals representing the displacement of the right ventricular endocardial wall are generated. Then, the algorithm uses the cross-correlation of the motion signals to estimate the contraction delays within the right ventricle (intraventricular synchronicity) and the contraction delay between the right and left ventricles (interventricular synchronicity).

The analysis of the contraction behavior analysis of healthy and left bundle branch block (LBBB) subjects is used for the validation of the algorithm. The algorithm’s ability to identify either group is considered as the major evaluation criterion. The results show that the healthy subjects have a stable septum which thickens during LV systole. LBBB patients have a thinner septum which exhibits a passive motion driven by the interventricular blood pressure gradient. This results in inconsistent radial displacement measurements. Also, the results show that in LBBB the right ventricular endocardium is activated before the left ventricular endocardium whereas in healthy subjects the LV activation occurs first.

This project has been developed in cooperation with the departments of Cardiology and Radiology of the Catharina hospital in Eindhoven (The Netherlands).
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1 Introduction

Cardiac disease is the principal cause of death in the developed countries. Consequently the assessment of normal and pathological heart behavior is an active research area.
Abnormal motion of the right ventricle (RV) indicates several types of cardiac disease, including ischemia and hypertrophy. However, it has not yet been well investigated because of the difficulties encountered due to wall thinness (3mm), complex geometry, and regional variations in contraction patterns.
The efficiency of the ventricular contraction is strictly related with its synchronicity. Most of ventricular myocardium movements are synchronous, but some diseases can lead to a loss of synchronicity. When the cardiac asynchronicity becomes severe, a resynchronization therapy, i.e., a pace maker implantation is needed.
The severity of the asynchronicity is usually estimated by the QRS time interval in the ECG recording. However, this measurement is not always a reliable index and does not provide any insight on the localization of the asynchronicity.
The goal of this study is to design a method capable of tracking the RV endocardium during one cardiac cycle in order to provide a spatio-temporal analysis of the RV contraction by using short axis Magnetic Resonance Images (MRI) cine-loops at high frequency. From this information, the analysis of the cardiac synchronicity is performed. The study data inputs available are cardiac MRI cine-loops of healthy subjects, used as a test group, and cine-loops of patients suffering of Left Bundle Branch Block (LBBB). These images were provided by the departments of Cardiology and Radiology of the Catharina hospital of Eindhoven (Netherlands).
This study consists of the following chapters:

Chapter 1 describes the cardiac anatomy and physiology. Also it provides an introduction of to the two types of heart diseases: ischemic cardiomyopathy and dilated cardiomyopathy. These diseases are particularly interesting for the present study because part of the used data input belongs to the patients suffering from LBBB caused by ischemic and dilated cardiomyopathy.

Chapter 2 enumerates the different techniques used to asses the RV function and presents a brief description of the MRI imaging technique used to obtain the data input.

In Chapter 3, the method proposed to perform the RV segmentation is described. This method starts with the Region of Interest (ROI) definition. Then, an edge detection based on thresholding is performed. Finally, in order to regularize the edge detection, the use of graph theory is proposed [13].
In Chapter 4, the RV regional wall motion from the literature available is summarized. Then, a study of the RV wall motion is also performed from the results obtained from the method proposed.

Finally, Chapter 5 studies the RV intraventricular (IV) synchronicity and the interventricular synchronicity.
2 The Heart

2.1 Anatomy: the study of organ structures

The heart is located between the lungs in the thoracic cavity. Fig. 1 shows the anatomy of the heart.

The heart consists in four cavities, the left atrium (LA), right atrium (RA), left ventricle (LV) and RV.

The atria are separated from the ventricles by the annuli fibrosi. The left and right atria are separated by the intra-atrial septum. The LV and RV are separated by the intraventricular septum (IVS) that is considered to be a part of the LV.

The geometry of the LV may be considered as a thick-walled truncated ellipsoid. However, the geometry of the RV is more complex [1]. The RV is a thin-walled chamber with crescent shape in cross section approximating a pyramid with...
a triangular base longitudinally. Inside the RV two different parts can be recognized: an inflow tract and an outflow tract, separated by the *crista terminalis*.

**BLOOD VESSELS**

Deoxygenated blood from the body enters into the RA through two great veins, the superior vena cava, which drains the upper part of the body, and the inferior vena cava that drains the lower part. The blood then passes through the tricuspid valve to the RV. The RV pumps the deoxygenated blood to the lungs, through the pulmonary artery. In the lungs gaseous exchange takes places and the blood releases carbon dioxide into the lung cavity and picks up oxygen. The oxygenated blood then flows through the pulmonary veins to the LA. From the LA this newly oxygenated blood passes through the mitral valve to enter the LV. The LV then pumps the blood through the aorta to the entire body.

**LAYERS OF THE HEART**

The wall of the heart has three layers: the outer epicardium the middle myocardium, and the inner endocardium. The epicardium is the smooth and visceral layer of the pericardium. The endocardium is a thin layer of endothelium deep to the myocardium that lines the chambers of the heart and the valves. It is irregular due to the existence of the trabecular layer that is the 30% of the endocardial wall thickness.

**VALVES**

The valves of the heart maintain a unidirectional flow of blood by opening and closing depending on the difference in pressure on each side. There are four valves in the heart:

- The two atrioventricular (AV) valves that prevent backflow from the ventricles into the atria during systole. They are attached to the wall of the ventricle by chordae tendinae. The chordae tendinae is attached to papillary muscles. Papillary muscles cause tension to better hold the valve. Together, the papillary muscles and the chordae tendinae are known as the subvalvular apparatus. The valve placed between LA and LV is called
mitral or bicuspid valve. The valve placed between RA and RV is called tricuspid valve.

- There are two semilunar valves present in the arteries leaving the heart, and they prevent the flowback of blood from the arteries into the ventricles. The valve placed between LV and aorta is the aortic valve. The valve placed between RV and the pulmonary artery is the pulmonic valve.

CONDUCTIVE SYSTEM

The heart has two systems that generate rhythmical impulses to cause rhythmical contraction of the heart muscle and conduct these impulses rapidly throughout the heart. Fig. 2 shows the different parts of the conductive system of the heart.

The three important parts of the heart's conductive system are:

- **Sinoatrial (SA) node:** The SA node is a small muscle located in the upper wall of the RA. The fibers of the SA node have the capability of self-excitation and they conduct the cardiac impulses towards the remainder of the heart.
• **AV node:** The AV node is the barrier between the atria and ventricles. The electrical signals are conducted from the atria to the ventricles through the AV node. The AV node delays the cardiac impulse transmission permitting the atria to empty their contents into the ventricles.

• **Purkinje system:** conducts the electrical signals from the AV node throughout the ventricles. The signal first reaches the bundle of His that is the extension of the AV node that passes into the IVS. When the His bundle is excited, the impulse moves down through the left and right bundle branches to the left and right septum. The bundles gives rise to the Purkinje fibers. These fibers are thin filaments that distribute the impulse into the ventricular muscle and make the ventricle to contract. The Purkinje system allows [2] the almost simultaneous activation at multiple sites on the endocardial surface. Then, the propagation of the signal in the myocardium is transmural, from endocardium to epicardium. In the absence of the Purkinje system, the excitation front would propagate somewhat radially form the point of stimulation in the most basal portion of the septum. This behavior would attach abnormal performance of the ventricular function.
2.2 Physiology: the study of organ function

![Diagram showing cardiac cycle phases]

**Figure 3:** The events of the cardiac cycle, showing changes in the aortic pressure, left ventricular pressure, left atrial pressure, ventricular volume (LV vol), the electrocardiogram (ECG) and the phonocardiogram (heart sounds).

The single cycle of cardiac activity can be divided into two basic stages. The first stage is diastole, which represents ventricular filling and a brief period just prior to filling at which time the ventricles are relaxing. The second stage is systole, which represents the time of contraction and ejection of blood from the ventricles.

To analyze these two stages in more detail, it is convenient to divide the cardiac cycle into seven phases is convenient. The cardiac cycle is divided into these phases according to the electrocardiogram (ECG)’s waves.

An ECG is a test that records the electrical activity of the heart. In Fig. 3, an ECG is showed. First appear the P wave (atrial depolarization), then the QRS
complex (ventricular depolarization) and finally the T wave (ventricular repolarization).

In this subdivision of the cardiac cycle, the first phase begins with the P wave in the electrocardiogram. The last phase of the cardiac cycle ends with the appearance of the next p-wave.

The cardiac cycle is defined for the follow phases:

1. **Atrial Contraction**

   The P wave is generated in the SA node. This wave spreads rapidly through the atria causing the atrial depolarization, the reason why the atrial musculature contracts. As the atria contract, the pressure within the atrial chambers increases so that a pressure gradient is generated across the open AV valves, thereby causing a rapid flow of blood into the ventricles. However, atrial contraction causes a small part of the ventricular blood filling because most of the ventricular filling occurs before the atria contract and therefore is passive. After the atrial contraction is complete, the atrial pressure begins to fall causing a pressure gradient reversal across the AV valves. This causes the closure of the AV valves in the time when ventricular volumes are maximal.

   The period of zero voltage in the ECG after the P wave represents the time in which the impulse is traveling within the AV node (where the conduction velocity is greatly retarded) and the bundle of His.

2. **Isovolumetric Contraction**

   The isovolumetric contraction phase starts with the beginning of the QRS complex. The QRS complex represents ventricular depolarization. The wave arrives to the bundle of His and spreads in the ventricles through the Purkinje fibers. That produces the ventricular contraction, the development of the ventricular wall tension and the rapid increase in IV pressure. When the IV pressure exceeds the atrial pressure, the AV valves close. During the time period between the closure of the AV valves and the opening of the semilunar valves, ventricular pressure rises rapidly without a change in the ventricular volume. This is the reason why the phase of ventricular contraction is called “isovolumic” or “isovolumetric”.

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3. **Rapid Ejection**

When the IV pressure exceed the pressure within the aorta and the pulmonary artery, the aortic and pulmonic valves open and blood is ejected out of the ventricles. Atrial pressure initially decreases, as the atrial base is pulled downwards, expanding the atrial chamber. Blood continues to flow into the atria from their respective venous inflow tracts.

4. **Reduced Ejection**

Approximately 150-200 msec. after the QRS, ventricular repolarization occurs (T wave). This causes ventricular active tension to decrease and the rate of ejection to fall. Ventricular pressure falls slightly below the outflow tract pressure whereas atrial pressures gradually rise due to venous return.

5. **Isovolumetric Relaxation**

When the total energy of the blood within the ventricles is less than the energy of the blood in the outflow tracts, the aortic and pulmonic valves close abruptly. Valve closure is associated with a small backflow of blood into the ventricles and a characteristic notch in the aortic and pulmonary artery pressure tracings. Ventricular pressure decrease but the volumes remain constant because all valves are closed. Atrial pressures continue to rise due to venous return.

6. **Rapid Filling**

When the ventricular pressures fall below the atrial pressures, the AV valves open and ventricular filling begins. The ventricles continue to relax despite the inflow, which causes the IV pressure to continue to fall. The opening of the AV valves causes a rapid fall in the atrial pressures.
7. Reduced Filling

As the ventricles continue to fill with blood and expand, they become less compliant and the IV pressure rise. This reduces the pressure gradient across the AV valves so the filling rate falls. Aortic pressure and pulmonary arterial pressure continues to fall during this period.

2.3 Heart diseases

On type of heart disease is the cardiomyopathy. The heart of a patient with cardiomyopathy becomes abnormally enlarged thickened and stiffened. As a result, the heart muscle’s ability to pump and receive blood is usually weakened.

Often, Physicians classify cardiomyopathies in two main groups: ischemic (resulting from a lack of oxygen) and nonischemic (the causes for which are not established):

- Ischemic cardiomyopathy is a chronic disorder caused by either recurrent heart attacks or coronary artery disease. The heart muscles of a ischemic heart not receive enough oxygen-rich blood. Ischemic cardiomyopathy is the most common type of cardiomyopathy.

- Non-ischemic cardiomyopathy includes three main types are: dilated, hypertrophic, and restrictive. The name of each describes the nature of its muscle damage.

  - Dilated cardiomyopathy involves dilation or enlargement of the heart’s ventricles and is usually accompanied by an increase in the cardiac mass. This often affects young people. Dilated cardiomyopathy physically resembles the ischemic cardiomyopathy.

  - Hypertrophic cardiomyopathy involves an abnormal growth of muscle fibers in the heart muscle, usually in the LV.

  - In Restrictive cardiomyopathy, the heart muscle cannot adequately relax after contraction, making it unable to fill completely with blood.
These diseases can lead to disorders related with the conductive system as LBBB. LBBB patients have the left bundles branch of the Purkinje system blocked and the impulse generated in the SA node cannot spread into the ventricles in a normal way.

The usual way to diagnosis a LBBB is by measuring the duration of the QRS complex. It is considered that a patient has LBBB disease when this complex is larger than 110ms. The QRS complex gives us the measure of total ventricular asynchronicity.

More detailed quantitative information about electrical asynchronicity is obtained using endocardial electrical mapping techniques [3]. With these techniques it is possible to obtain two indicators of ventricular asynchronicity. One of them is the IV synchronicity. This measure provides us with information about the delay correlation between points in the ventricle and it is performed for each ventricle independently. Also, the interventricular asynchronicity can be measured. This measure provides us with information about the delay correlation between RV and LV.

The features of LBBB interventricular and IV asynchronicity have been studied in detail in numerous studies [3], [4], [5], [6]. In patients with LBBB,

- RV contraction occurs before initiation of LV contraction whereas in healthy subjects the LV activations occur before the RV activation.
- LV endocardial activation most likely occurs as a result of right-to-left transseptal activation.
- LV endocardial activation sequence in patients with LBBB is heterogeneous whereas in healthy subjects the LV endocardial activation sequence is homogeneous due to the action of the Purkinje system.
- RV endocardial activation in patients with LBBB is not affected.
3 Assessment of right heart function

Early studies used implanted radiopaque markers to provide information about RV motion. These studies were usually performed on animals giving a limited knowledge about the RV motion and geometry. This technique needs to implant radiopaque markers in some regions of the RV wall, making it uncomfortable for the patient.

Recently, non-invasive imaging techniques have provided new means to study the RV. Radionuclide techniques, computed tomography, cardiac catheterisation, Doppler Echocardiography are some of these techniques. MRI has been also used recently providing accurate assessment of regional RV wall motion and chamber size. The availability and cost are the main limitations for this technique.

3.1 Magnetic Resonance Imaging

Nuclear magnetic resonance (NMR) is a non-invasive means of obtaining clinical images for studying tissue metabolism in vivo. Bloch and Purcell independently discovered NMR in 1946. Six years later, they were awarded the Nobel Prize for their achievements. Since then, the development of NMR spectrometers and NMR scanners paved the way for new investigations in the branches of physics, chemistry, biology and medicine.

The process of acquiring two and three-dimensional (3D) images by NMR, known as magnetic resonance imaging (MRI), was first illustrated by Lauterbur (1973) who achieved two-dimensional (2D) images produced using the relative positions of magnetic resonant behaviors among protons in a phantom.

Over the last 20 years, Fourier transform imaging techniques have tremendously accelerated the development of MRI.

MRI imaging exploits the property of certain atomic nuclei to vibrate when exposed to bursts of magnetic energy. The atomic nucleus used for this technique is the single proton that forms the nucleus of a hydrogen atom. The nucleus of a hydrogen atom was chosen because it is present in water molecules \((H_2O)\), which are present in every tissue in the body. When the hydrogen nuclei resonate in response to changes in a magnetic field, they emit radiofrequency energy. The MRI scanner detects this emitted energy, and converts it into an image. The tissues of the body contain different quantity of water. Blood contains 79% of water, the cardiac
muscles of 75% and the lung of 70%. Each tissue in MRI images has a different gray intensity level according to the concentration of water. For this reason, in MRI images, the myocardial muscle and the ventricle cavities (blood pools) are represented by different gray intensities. This property served to perform the RV segmentation in the next chapters.

Fig.4 shows an example of cardiac MRI image.

Figure 4: A MRI image is shown.

3.2 Cardiac MRI Segmentation

In [7] segmentation problems of the heart are divided in the three most important:

- The information of MRI images could not be well defined due to the presence of noise during image acquisition. For this reason, human observers can trace the contour but many automatic techniques could fail.
- In image segmentation, a strong difference of intensity between tissues (i.e., contrast) is needed. The presence of papillary muscles in the cavity and fatty tissues around the walls of the ventricles can cause a problem in image segmentation.
- There are many segmentation techniques that require user inputs to provide the initial conditions for a segmentation algorithm in the form of a seed point or initial boundary model.
3.3 Short Axis View

In clinical imaging the terminology XY, XZ, and YZ are not used to indicate the imaged plane. Instead, the system shown in Fig. 5 is used. It is described as follow:

- **Coronal plane**: a plane bisecting the front of the body from the back.
- **Sagittal plane**: a plane bisecting the left and right sides of the body.
- **Axial plane**: a plane perpendicular to the coronal and sagittal planes.

![Coronal, Sagittal, and Axial Planes](image)

**Figure 5**: *The planes used for the body in MRI imaging are shown.*

The cardiac planes generated by using the long axis of the body (axis passing through the neck, thorax, abdomen, and pelvis) do not cleanly transect the ventricles, the atria or the myocardial regions. Therefore, The American Heart Association [8] recommends using a different reference system. They have defined and oriented the heart for display at 90° relative to the long axis of the LV that transects the apex and the center of the mitral valve plane. According to this reference (slope), the short, vertical long and horizontal long axis planes are defined in the same way as those defined for the rest of the body. Fig.6 shows this planes.
For regional analysis, the heart is divided into equal thirds perpendicular to the long axis of the heart. This generates the basal region, the mid-cavity region and the apical region:

- **Basal region:** the area extending from the mitral annulus to the tips of the papillary muscles at end diastole.
- **Mid-cavity region:** the region that includes the entire length of the papillary muscles.
- **Apical region:** the area beyond the papillary muscles to the cavity ends.
4 Right Ventricle Segmentation

Segmentation involves separating an image into regions corresponding to objects. We usually try to segment regions by identifying common properties. The simplest property that pixels can share in a region is the intensity; therefore, a natural way to segment such regions is through thresholding by separating light and dark colored structures.

Threshold calculation involves choosing a gray level T such that all gray levels greater than this level are mapped into the “object” and all other gray levels are mapped into the “background”.

The proposed method limits the analysis to an area that encloses both ventricles. Thresholding is then applied to this region identifying both cavities as a foreground of the image. Subsequently, the edge detection is performed. Finally, edge regularization is obtained.

This method was also tested for the segmentation of LV with accurate results (See Appendix A).

4.1 Region of Interest definition

The ROI is the area of the image that contains the information to be analyzed. The ROI used for RV segmentation was a circle containing both ventricles. To build this ROI, we used a binary image that represents the motion in the MRI sequence and the LV center point. This information was obtained from the initial steps of the method proposed in [9] for LV segmentation. This method starts computing the variance for each pixel of the complete MRI sequence. High variance values represent high motion of the pixel in the sequence whereas low variance values represent low motion. These values are then mapped in a grey scale obtaining a gray scale image. In this way, this image provides information about the motion in the MRI sequence. The Otsu threshold is subsequently applied to this image. As a result of this process, a binary representation of the motion of the heart is obtained. Finally, this image is used to obtain the LV center. As this method assumes that the LV shape can be tracked during the cardiac cycle over a set of concentric circles, the Hough transform is used to obtain the LV center and radius.

Once the binary image and the LV center is available, an iterative algorithm is used to construct the ROI. The smaller circle containing the majority of the white pixels of the image is determined. This circle is centered in the center of mass of the binary image.
The algorithm computes the number of white pixels enclosed in a circle. First it starts with the estimation of a radius sufficiently large to enclose both ventricles. Then it decreases this radius and computes the number of white pixels again. When the difference of white pixels between two consecutives circles has a value greater than a threshold established, the algorithm stops. This threshold makes the algorithm stops when the difference of white pixels between two consecutives circles is higher than 10 pixels.

The outcome of this algorithm is presented in Fig. 7. This circumference delimits the ROI used as a mask in all the following steps.

![Circle obtained with the iterative algorithm](image)

**Figure 7: Circle obtained with the iterative algorithm**

### 4.2 Edge Detection

One way to obtain a threshold that separates two objects in a picture is by using clustering-based thresholding methods. One of the most referenced thresholding methods is the Otsu threshold [10]. The Otsu threshold gives satisfactory results when the number of pixels in each class is almost equal.

This threshold calculates the between-class variance for each potential threshold T. First the histogram is divided into two clusters of pixels by the threshold T. Then, the mean of each cluster is found and the difference between this means is squared. This difference is multiplied by the number of pixels in one cluster and by the number of pixels in the other.

Finally, the threshold that maximizes the between-class variance is chosen.
A picture is represented in $L$ gray levels $[1, 2 \ldots L]$. The number of pixels at level $i$ is denoted by $n_i$ and the total number of pixels by $N = \sum_{i=1}^{L} n_i$. $N$ is used to normalize the gray level histogram:

$$p_i = \frac{n_i}{N} \tag{1}$$

The probabilities of class occurrence ($\omega_0, \omega_1$) and the class mean levels ($\mu_0, \mu_1$) are given by,

$$\omega_0 = \sum_{i=1}^{k} p_i \quad \omega_1 = \sum_{i=k+1}^{L} p_i \quad \mu_0 = \sum_{i=1}^{k} \frac{ip_i}{\omega_0} \quad \mu_1 = \sum_{i=k+1}^{L} \frac{ip_i}{\omega_1} \tag{2}$$

$k$ is the possible threshold evaluate in each moment.

The total mean level of the original picture is

$$\mu_T = \sum_{i=1}^{L} ip_i \tag{3}$$

The between class variance is defined as

$$\sigma^2_b = \omega_0 (\mu_0 - \mu_T)^2 + \omega_1 (\mu_1 - \mu_T)^2 = \omega_0 \omega_1 (\mu_1 - \mu_0)^2 \tag{4}$$

Finally, the threshold that maximize the between class variance is,

$$\sigma^2_b(k^*) = \max_{1 \leq k \leq L} \sigma^2_b(k) \tag{5}$$
A MRI image has different gray intensities that correspond to different tissues. Fig. 8 shows the histogram that corresponds to a MRI image. In this histogram, different objects or classes can be observed. There is a quantity of black pixels (intensity value of 0) that corresponds to the background of the MRI image (the part of the MRI image that is not part of the body). There is a quantity of white pixels (intensity value of 255) that corresponds to the additional information about the slice. The rest of the peaks correspond to the different types of tissues present in the MRI image.

![Histogram of a MRI image.](image)

For calculating an accurate threshold that separates all the tissues observed in the MRI, the histogram is complicated. In order to do this task easier, we propose to use a mask that enclose only the LV cavity and the LV wall. Thus, only two types of objects (the blood pools of the cavity and the myocardium) are considered. We assume that the gray intensity in LV and RV cavities and the gray intensity of the LV and RV walls should be approximately equal in both ventricles. In this way, this threshold can be used to segment both cavities. To construct this mask we use the LV center point and the radius obtained in [9]. Then, this mask is applied to the MRI to construct the histogram of gray levels. This histogram is used to calculate the Otsu threshold.

Since this mask is fixed across the set of MRI during systole, when the ventricle is more contracted and the wall is thicker, the number of pixels for each class varies. This can be a problem for the threshold calculation because the Otsu
threshold obtains better results when the number of pixels of the objects are about the same.

The example of the mask applied is shown in Fig. 9A). Fig. 9 B) shows the portion of the MRI used to construct the histogram of pixels.

![Image of mask and MRI section](image)

**Figure 9:** A) Mask used to obtain the histogram used by the Otsu threshold . B) Image outcome to apply the mask of figure 17 A) in the MRI image.

Fig. 10 shows the histogram corresponding to the MRI image after applying the mask. The lobe centered in the value of intensity 80 corresponds to the LV wall. The other lobe corresponds to the LV cavity. In systole time, the amplitude of the first lobe increases whereas the amplitude of the second lobe decreases. This is caused by the growth of the LV wall and the consequent decrease of the LV cavity.

![Histogram of MRI image](image)

**Figure 10:** Histogram of the MRI image after apply mask.
Fig. 11 shows the image obtained applying the Otsu threshold to the MRI image.

Figure 11: The outcome of applying the Otsu threshold in a MRI image is shown.

Another way to obtain the threshold for RV segmentation has been tested. An example is shown in the appendix B, where a threshold based on the features of the IVS is proposed.

The intensity level of the muscles vary among the MRI images sequence. The gray intensity of the myocardium usually is higher during the systole than during the diastole. Therefore, for each image of the MRI sequence, a different threshold is used.

The following figures correspond to the intensity values of a horizontal line in one MRI image. This line has as Y coordinate the Y coordinate of the LV centre.

Fig. 11 shows a MRI image at ventricular systole. In this phase the contraction of the muscles (myocardium) of the LV and RV takes place and the LV wall is thicker.

Fig. 12 shows a MRI image during ventricular diastole. In this phase, the LV wall is thinner.
Figure 12: In the figure the profile of intensity corresponding to a horizontal line of an image MRI is seen.

Figure 13: The figure shows an intensity profile of one MRI image among one horizontal line which Y coordinate as Y coordinate of LV center point. The MRI image corresponds with a phase of ventricular diastole.

Finally, an edge detector is applied to the binary images obtained. A set of rays whose origin is the LV center is obtained. These rays have equiangular distance of 2 degrees. This angular distance is selected in order to provide with enough accuracy the detection of the wall. These edges points are determined based on the contrast and slope of the binary image.
Fig. 15 shows an example of the edge detector used for the segmentation.

![MRI image showing the set of rays centered in the LV centre and the points selected for RV segmentation](image)

**Figure 14:** MRI image that shows the set of rays centered in the LV centre. The points showed in the picture represent the points selected for the RV segmentation.

The RV can be described as a half-moon attached to the circular LV. Thus, it can be assumed that the RV consists of two arches connected to their extremes. If we work with circular shapes, a change into polar coordinates can transform a 2-dimensional problem into a 1-dimensional problem. Therefore, in order to simplify the following calculations, the Cartesian coordinates of the edges points are transformed into polar coordinates centered in the LV center point.

The coordinate system is shown in Fig. 14.

![Coordinate system with origin LV center](image)

**Figure 15:** Coordinate system used to obtain the set of rays with origin LV center.
Fig. 16 shows the edges detected in polar coordinates.

**Figure 16:** The image shows the points detected along the radius. The three first edges detected correspond to the IVS and the RV free wall.

The points detected have been divided into sets. Each set corresponds to different tissue represented in the cardiac MRI image.

In summary, the detected edges along the rays, starting from the LV center point, can be grouped in the following three subsets:

- **LV wall (first edge):** the horizontal line spreads in the entire domain of the image. This line represents the LV wall because the LV centre is used as the origin of the edge detection.

- **RV wall(second and third edges):** the closed curve situated on the top of the LV wall. We assume that this curve is composed of two lines: the lower line (second edge) corresponding to the RVS wall and the upper line (third edge) corresponding to the RV free wall.

- **Points belonging to papillary muscles and fat tissue:** the points belonging to the papillary muscles can be found below the LV wall and inside the RV wall (inside both cavities) whereas the points belonging to the fat tissue can be found on top of the LV wall and RV free wall.
If there are presence of fat tissues in the surroundings of the heart, additional white pixels appear in the binary image. If there are presence of papillary muscles, holes inside both the cavities appear because they show similar intensity to the myocardium. These structures result in undesirable edge points and should be regularized.

4.3 **Regularization of the edge detection**

For the RV synchronicity analysis, only a limited segment of the RV boundary is used. This segment is the RV region with RV free wall quasi-parallel to the IVS. We assume that this sector of the RV contains most of the RV area and, therefore, can reliably be used for the synchronicity analysis.

To determine the region where the RV free wall is quasi-parallel to the IVS, the difference between the second and third set of points (associated with the RVSW and the RVFW) is computed (Fig. 16A). Then, these points can be easily smoothed by using spline functions [11] or applying a low pass filtering.

In Fig. 17A) this difference between third and first bound after smoothing is shown. The RV cavity is located between $150^\circ$ and $270^\circ$. This is assumed because this interval shows the highest difference between these two bounds. It can be observed that around the point with the maximum amplitude the curve is flatter because the RV wall is quasi-parallel to the IVS. On the contrary, in the extremes of this region the amplitude decreases rapidly. The extremes decrease until 0, which represents the end of the cavity. The point with higher amplitude in Fig. 17A) is calculated for all the frames obtaining a set of cavity center angles for all the frames.

Finally, the first derivative of this curve is calculated in order to obtain the extremes of the RV wall segment. Fig. 17 B) shows the first derivative of these points. The higher peak corresponds to the angle at which the RV free wall becomes parallel to the IVS ($\theta_{\text{start}}$) and the lower valley to the angle in which the RV free wall stops being parallel to the IVS ($\theta_{\text{end}}$). We compute these two angles in all the frames. In the superior and inferior parts of the ventricles usually there are presence of fat tissues. This often causes wrong detection of the start angle and end angle. In order to the select a suitable end and start angles, the following process then is performed:
1. The mean of the set of center angles is calculated. $\theta_{\text{global}_\text{center}}$

2. The end angles belonging to the interval $[\theta_{\text{global}_\text{center}} + \frac{\theta_{\text{min}_\text{cavity}}}{2}, \theta_{\text{global}_\text{center}} + \frac{\theta_{\text{max}_\text{cavity}}}{2}]$ are selected as possible end angles. The end angles bigger than these values are selected as possible end angles. From this subset, the lower end angle is selected as end angle of the cavity, $\theta_{\text{end}_\text{center}}$.

3. The start angles belonging to the interval $[\theta_{\text{global}_\text{end}} - \theta_{\text{max}_\text{cavity}}, \theta_{\text{global}_\text{end}} - \theta_{\text{min}_\text{cavity}}]$ are selected as a possible start angles. From this subset, the maximum start angle is selected as start point, $\theta_{\text{global}_\text{start}}$.

The selection of the interval also permits to define the minimum angular and the maximum amplitude of the cavity. Usually, this minimum and maximum amplitude of the cavity are fixed in $60^\circ$ and $160^\circ$ respectively.

These angles define the segment of the wall used to perform the synchronicity analysis.

---

**Figure 17:** A) Distance between second and third wall corresponding with IVS wall and RV wall respectively. B) First derivative of the polar plot in Fig. A)
The results demonstrated that 87% with a standard deviation of 20% is covered and, therefore, the method is sufficiently accurate for further analysis, e.g. ROI definition for the synchronicity analysis.

The papillary muscles have to be excluded from the endocardial boundary if the final goal of the image processing is the quantification of the cardiac function according to the standards recommended by the American Society of Echocardiography [12].

After the edge detection a set of possible points belonging to the edges of the RV cavity is obtained. Usually, the first two edges correspond to the IVS walls and the third edge belongs to the RV free wall. However points coincident with the papillary muscles and with areas of high gray value in the surroundings of the heart appear. In order to overcome the errors in RV free wall detection produced by the presence of the papillary muscles and the fat tissue, graph theory is used.

Graph theory was used in the method proposed in [13] called intelligent scissors. They use the live-wire tool that allows the user to interactively select an optimal boundary segment by immediately displaying the minimum cost path from the current cursor position to a previously specified “seed” point in the image. This method provides accurate results, but needs the action of the user to select the start point. The present method adapts the use of the shortest path to regularize the point obtained from the edge detection. This algorithm allows us to separate the points belonging to the papillary muscles and the fat tissue from the points belonging to the RV walls.

4.4 Shortest path algorithm

In order to calculate the RV walls, a matrix of edge points is used as the input of the shortest path algorithm. This matrix (showed in Fig.18) contains the points obtained in the edge radial detection. The columns index corresponds to the angles at which the detection is performed. The rows index corresponds to the order in which the elements were found. N is the number of radial lines used to detect the edges of the binary images. Thus, in case the Right Ventricle Free Wall (RVFW) segment starts at angle $\theta_1$ and ends at angle $\theta_2$.

$$N = \frac{\theta_2 - \theta_1}{2}$$  \hspace{1cm} (6)
First, the set points which have more probability to belong to the bound desired are established. These points are used as a start point for the shortest path algorithm. The two set of points chosen are: the second set for the RVS wall regularization, whereas the third set for the RV free wall. They form the second and the third row of the matrix respectively.

Frequently, the presence of the papillary muscles leads to a wrong detection. If a point which belongs to the papillary muscles is chosen as start point, the outcome of the shortest path algorithm would be wrong.

In order to avoid these problems, the shortest path algorithm is executed for all the starts point in the second and the third rows of the matrix. Under the assumption that the papillary muscles are not spread along the complete cavity, a point that belongs to the boundary of the cavity is chosen at least once. The shortest path containing this point belongs to the RV free wall or IVS wall.

**Figure 18:** *The arrays of starts points for the shortest path algorithm.*

Once the set of possible start points is selected, the algorithm computes the next steps for each of these points (N times).
1. **Select point**

A start point from the set of possible starts points is selected, assuming that these points belong to the desired boundary.

2. **Find nearest adjacent point**

   In order to find the shortest path, the nearest adjacent point to the start point selected is chosen.

   Once this point is found, the distance between the two points is added to the total distance of the path and this last point is established as the new start point for the next iteration. Fig. 19 illustrates the selection of the nearest adjacent point.

![Figure 19: Selection of the nearest adjacent point.](image)

3. **Repeat two**

   The second step is then repeated in the both directions (left and right) until the point that corresponds to the start and end angle respectively is reached.

4. **Execute 1-3 for a different start point**

   Steps 1-3 are executed for all possible start points. When the shortest path is calculated for all the start points, a matrix with N possible paths and an array with its N corresponding lengths are obtained.

5. **Select path**

   Finally, the path with minimum length is selected.
Fig. 20 shows all the edges detected from the MRI and the paths selected as RVFW and (right ventricle septum wall) RVSW. In the figures, these paths are traced with a line. In Fig. 20 A) the line traced corresponds to the IVS wall. In Fig 20B), the line traced corresponds to the RV free wall.

In these cases, the shortest path is able to eliminate the papillary muscle from the definition of the RV walls resulting in an accurate definition of the RV walls.

**Figure 20:** Set of possible points obtained after thresholding. Fig. A) shows the IVS wall obtained applying the shortest path algorithm. Fig. B) shows the RV free wall obtained applying the shortest path algorithm.
Sometimes, the path achieved with the algorithm presents some discontinuities. These discontinuities appear because of two main reasons:

1. The shortest path used in the definition of the RV walls usually excludes the papillary muscles. However, the shortest path algorithm assumes that the papillary muscles belong to the myocardium if the papillary muscles are connected to the endocardial wall.

2. The fatty tissue surrounding the RV generates undesirable points in the surroundings of the cavities. If the (right ventricle free wall) RVFW is thin, these points could be very close to the endocardial wall. Therefore, the algorithm could fail and to chose these points.

The cardiac contour is continuous and smooth. Also, it has continuous motion in time. This motion has sinusoidal behavior, with the lower value at the time of contraction and the highest value at the time of relaxation of the muscles. In order to re-establish this continuity, space and temporal filtering is use. The filters used are FIR low-pass filters with 15 taps and the low pass frequency is adjusted in order to assess the best results.

4.5 Segmentation results

In Fig.21 the outcome of the proposed method is shown.

Figure 21: The contour detection of the RVFW and the RVSW is shown.
In order to prove the accuracy of the method, a set of fifty MR images are randomly selected from the available MRI images. Automatic and manual contour detection are performed. Then, the results obtained are compared in the following figures.

Fig.22 shows the correlation between the manual and the automatic methods in 50 images. The correlation coefficient is 0.977.

![Figure 22](image)

**Figure 22:** Automatic versus manual areas measured in number of pixels.

The comparison between the manual and the automatic contour detection is also shown by the Bland-Altman plot in Fig.23. The percentage of difference between manual and automatic segmentation is 5.1% with a standard deviation of 7.5%.

![Figure 23](image)

**Figure 23:** Bland-Altman plot of the area estimates by automatic and manual contour detection.
Finally, Fig. 24 shows the percentage of area error. This area error was calculated computing the XOR between the manual and the automatic segmentation. The results display a mean area error of 13% with a standard deviation of 3%.

**Figure 24:** The histogram of the percent area error between automatic and manual measurements for 50 MRI images
5 Review of the right ventricle wall motion

The RV cavity volume decreases during systole due to a combination of the following mechanisms [14]: motion of the free wall towards the septum, motion of the base toward the apex and the bulging of the septal wall into the cavity.

The biventricular unit exhibits initial clockwise rotation, followed by a twisting of the base with respect to the apex. In [15] is assumed that the cause of these clockwise and counter clockwise rotations is the "wringing motion" of the LV ventricle, which pulls the RV. This "wringing motion" is characterized by a clockwise contraction of the LV at the base and a counterclockwise rotation at the apex. Also, a contribution of the LV in the right ventricular function through the interventricular septum (IVS) is reported [15].

A study performed with MRI in short axis view, gives us some detailed information about the RV free wall motion [16]. As our data input are short axis views, this information can be used to understand the results obtained in the asynchronicity and regional wall motion study. In this study, because of the heterogeneous RV motion, the RVFW is divided into three wall segments (inferior, mid and superior) to allow for more detailed study of the contraction and motion. They concluded that the overall motion of the RVFW can be described as a wave of contraction towards the septum with motion towards the outflow tract as well in order to reduce the size of the blood cavity volume. In the three slices, an inferior motion, combined with an anterior motion in some wall segments is noted (Fig.26 define the direction of the inferior, superior, anterior and posterior motion). This motion provides a sometimes outward motion contrary to the trajectory seen in the rest of systole. They reported that this "rocking" motion may be important for the efficient cavity reduction by storing energy as a spring does for release during systole.

Also, different motion patterns are observed among the slices:

1. Mid-ventricular and apical slices: the superior wall showed an inferior motion throughout the systole whereas the inferior and mid-wall segments showed a superior motion from mid to end-systole.
2. Basal slice: Showed a different motion pattern in the superior segment due to the proximity of the right ventricular outflow tract and the accompanying rush of blood out of the cavity. This pattern is described by a inferior motion in the mid-systole followed by the relatively large superior motion in the late to end-systole.
Fig. 25 shows the average motion vectors obtained in [16]. These vectors were calculated for the apical, mid-cavity and basal slices.

**Figure 25:** Average motion vectors in the apical slice (left), the midventricular slice (center) and the basal slice (right).

### 5.1 Analysis of the regional wall motion

Once the segmentation of the complete cardiac cycle is performed for each frame, the distance between the LV center and the points detected in the RV wall is calculated. After that, for each point of the RV wall, a set of possible distances between the point and the LV center are available. These values can be plotted versus time giving us temporal information about the regional RV wall motion. The signal achieved has a quasi-sinusoidal shape. The higher value represents the end-diastole (ventricle dilated) and the lower value the end-systole (ventricle contracted). If the signal is repeated multiple times, a continuous harmonic motion can be simulated (see Fig.26).
5.1.1 RVFW analysis

Fig. 26 shows the motion signal of the complete RVFW segment. A different pattern of the motion is observed between the signals from different directions (angles).

![Figure 26: Overall of the RVFW motion signals.](image)

In order to analyze this motion, Fig. 26 is divided into three sub-plots. The subdivision is made according to the edge segments defined in Fig. 27.

![Figure 27: Division of the RVFW for RV motion analysis](image)
Fig. 28 plots the motion signal that corresponds to the upper part of the RVFW. Fig. 29 plots the part belonging to the middle of the RVFW and Fig. 30 corresponds to the bottom part of the RVF wall.

**Figure 28:** The motion signals belonging to the RVFW upper par are shown.

**Figure 29:** The motion signals belonging to the RVFW mid par are shown.

**Figure 30:** The motion signals belonging to the RVF wall bottom part are shown.
The three figures show a similar regional behavior of the RVFW. The difference in the shape of the signals is caused by different motion of the segments of this wall, the irregular shape of the ventricle and the selection of the LV center as a reference.

The signal also shows a “rocking” motion during the end of the diastole and the beginning of the systole. This motion agrees with the pattern of motion reported in [16] and showed in Fig.25.

During the end of the diastole, the signal shows a rapid increase. This could be caused by out-of-plane (longitudinal) motion of the ventricle. Therefore, as the RV has a crescent shape, a longitudinal motion of the RV could cause this rapid increase of the signal.

In some points, Fig.27 shows a completely different pattern of motion. This pattern is caused by the proximity of the basal slice to the RV outflow tract. In order to obtain accurate synchronicity results, the selection of a slice without the presence of the outflow tract is required.
5.1.2 RVSW analysis

Fig.31 A) and B) show the average of all the LVSW and the RVSW motion signals, respectively. During the complete cardiac cycle, LVSW and RVSW exhibited similar pattern of motion; during systole, they move through the center of the LV cavity and during diastole in the opposite direction. Fig.31 C) shows the difference between the average of the LVSW and the RVSW motion signals. During systole, an increase of this difference is observed because the LV wall thickens.

Figure 31: A) Average of the LVSW signal motion. B) Average of the RVSW signal motion. C) Average of the difference between LVSW and RVSW signal motion.
In LBBB patients, a different motion of the IVS was detected. For the assessment of this motion, the thickness in end-systole and end-diastole of the IVS was calculated. This measure was done for ten healthy subjects (test group) and ten LBBB patients. Fig. 32 A) illustrates that, for the test group in end-systole, the thickness of the IVS was always bigger than in end-diastole. Fig. 32 B) shows, in contrast, that in 5 of the 10 LBBB patients, the IVS thickened more during diastole than during systole.

**Figure 32:** Comparison of the IVS thickness during systole and diastole for the test group (upper plot) and LBBB patients (lower plot).
Also a measurement of the RVSW and of the LVSW “motion” was performed. For the assessment of this “motion”, the difference between the radius (in pixels) in end-systole and in end-diastole was calculated. Fig.33 shows these differences for 10 healthy subjects (A) and for 10 LBBB patients (B). The results demonstrate that, in healthy subjects the LVSW moves more than the RVSW. In contrast, 5 of the LBBB patients show a different behaviour, moving the RVSW more than the LVSW.

**Figure 33:** Difference between the RVSW and LVSW radius for the test group (upper plot) and LBBB patients (lower plot).
The results show that the healthy subjects have a stable septum which thickens during LV systole. LBBB have a thinner septum which exhibits a passive motion driven by the interventricular blood pressure gradient. This results in inconsistent radial displacement measurements.
6 Asynchronicity study

In order to estimate the synchronicity of the heart we need to know the delay of the electrical impulse throughout the heart. Fig. 34 shows these delays.

![Figure 34](image_url)

**Figure 34:** Transmission of the cardiac impulse through the heart, showing the time of appearance (in fractions of a second) of the impulse in different parts of the heart.

The impulse generated in the SA node spreads in the atria, taking around 0.07 s in to arrive to the AV nodal region. The impulse is then delayed in the AV nodal region for more than 0.1 s before appearing in the ventricular septal AV bundle. Once it has entered this bundle, it spreads rapidly through the Purkinje fibers to the entire endocardial surfaces of the ventricles. The excitation of the last ventricular muscle in both the ventricles occurs only 0.06 s after of the excitation of the first ventricular muscles. This causes all portions of the ventricular muscle in both the ventricles to begin their contraction almost simultaneously.
A known way to compare the similarity between two signals is the cross-correlation. Cross-correlation computes a measure of similarity of two input signals as they are shifted by one another. The cross-correlation result reaches a maximum at the time when the two signals match best. If the two signals are identical, this maximum is reached at $t = 0$ (no delay). If the two signals have similar shapes but one is delayed in time, then correlation is a good method to measure that delay. The cross-correlation $R_{xy}$ between two signals $x(t)$ and $y(t)$ is defined as:

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} x(t) y(t - \tau) \, dt$$

(7)

To calculate the IV and the interventricular synchronicity, two different types of measurements are performed:

6.1 Intraventricular synchronicity

In section (5) a different motion between the RVFW and the RVSW is shown. Therefore, the interventricular delay is calculated independently for the two walls of the RV.

Two signals, one from each wall, are chosen as the reference signals. The choice of these reference signals is not arbitrary [9]. The signal with the best signal-to-noise ratio (SNR) in each wall is selected. If the SNRs of two or more signals are equal, the signal with the maximum signal variance is selected.

$$\max_{\theta} (\text{SNR}(\theta) \cap S(\theta))$$

(8)

With:

- $\theta$ is the angle
- $\text{SNR}(\theta)$ is the normalized signal-to-noise ratio
- $S(\theta)$ is the normalized signal variance
The SNR is obtained from the signal before and after temporal filtering. Before temporal filtering, it was assumed that the signal has noise. After filtering, this noise is suppressed. Thus, the noise is calculated by subtracting the signal without noise (after the filter) to the signal with noise (before the filter). The SNR, which is the ratio between the variance of the signal after filtering and the noise is calculated.

Finally, for each wall, the reference signals are cross-correlated with the rest of wall segments. For each cross-correlation, the position of the highest value that represents the delay between this segment and the reference is chosen.

The results of this process are two plots of the frame delay versus the angle position.

Fig.35 shows an example of this measurement performed for the RVFW in a healthy subject. The picture shows that this delay is lower than two frames. In this patient, the time of acquisition was 10ms which results in a maximum delay of 20ms between the different segments of the RVFW. This agrees with the expected results, and proves that the RVFW contracts (in this case) in a synchronous way.

![Graph](image)

**Figure 35:** The delay between different RVFW segments in a healthy subject is shown.

The same measurement was performed for the RVFW in LBBB patients. Fig. 36 shows an example. Notice that the results obtained were similar to the results obtained for the healthy subjects. Therefore, a disease in the left bundle branch of the Purkinje system does not necessarily affect the RV synchronicity.
Spatio-temporal assessment of right ventricle dyssynchronicity by magnetic resonance short-axis cine-loop segmentation

Figure 36: The delay between different RVFW segments in a LBBB patient is shown.

In all the subjects, the frame delay measured was very sensitive to the complex shape of the RVFW. Therefore, making use the prior knowledge of the RVFW shape, a careful interpretation of this delay must be done.

The shift delay between RVSW segments was calculated. The same measurement was also done for the LVSW. The results were similar for both walls for healthy and LBBB patients. Also, the delay between the two segments, one belonging to the RVSW and the other to the LVSW, was calculated for each fixed angle. Once again, the results probed synchronicity between both walls in both healthy and LBBB subjects.

In Fig.37, an example of delay between different RVSW segments in healthy subjects is shown.

Figure 37: The delay between different RVSW segments in a healthy subject is shown.
6.2 Interventricular delay

For the assessment of the interventricular delay, a different measure is performed. First, the average of the RVFW signal motions and the average of the Left Ventricle free wall (LVFW) are calculated. Then, the delay between these two signals is calculated by computing the cross-correlation of the signals. A positive delay indicates that the LVFW is activated first, whereas a negative delay indicates that the RVFW is activated first.

This measurement was performed for ten healthy subjects and ten LBBB patients. Fig. 38 shows the delays obtained for each group of people.

Figure 38: The interventricular delay, expressed in % of cardiac cycle, is measured in the test group (healthy) and the LBBB patients.
From the results, we can conclude that in healthy subjects the LVFW is activated first than the RVFW, whereas in LBBB patients the activation of the RVFW occurs before the activation of the LVFW. These results are coherent with the results obtained by [3], [4], [5] and [6].

In [5], a more pronounced delay in patients with ischemic cardiomyopathy with respect to patients with dilated cardiomyopathy is found. From the data available, different interventricular delays between the patients were found, but we could not prove their relationship with specific cardiomyopathy dysfunctions.
7 Conclusions and future work

A fully automated segmentation technique to identify the RV endocardial wall from short axis MRI images was developed. This method allows tracking of the RV endocardium during one cardiac cycle and provides useful cardiac synchronicity information in a simple and quick way.

The RV cavity volume decrease during systole due to the motion of the free wall toward the septum, the motion of the base toward the apex and the bulging of the septal wall into the cavity.

An analysis of the regional wall motion was performed. The plane that is adopted to obtain the short axis cardiac MRI images is kept fixed during the acquisition process. Consequently, the out-of-plane motion of the ventricles can result in unexpected artifacts in the detected wall motion. The signal analysis shows a rapid increase during end-diastole and beginning systole. Probably, this is caused by the longitudinal motion of the heart. Moreover, during this period, a “rocking” motion was also noticed.

The IVS behavior was also studied by analyzing the motion of the RVSW and the LVSW. These two walls showed a similar motion: during systole they move towards the LV center whereas during diastole they move in the opposite direction. Nevertheless, in healthy subjects, a higher displacement of the LVSW toward the LV center was noticed. This action helps to empty the LV cavity and also provides the LV endocardium with more pumping power, necessary to pump the blood throughout the body. However, in some LBBB patients, a different behavior of the IVS was detected. In 5 of the 10 LBBB patients tested, the IVS thickened more during diastole than during systole. This was caused by a lost of motion of the LVSW.

In order to analyze the contraction timing of the RV, a measurement of the interventricular and interventricular synchronicity was performed by using cross-correlation. As expected, LBBB and healthy subjects showed similar delay between segments in the RVFW and RVSW. This demonstrates that a conduction defect in the left bundle of the Purkinje system does not necessarily influence the RV motion and timing. Nevertheless, in all the subjects, the frame delay measured was very sensitive to the complex shape of the RVFW. Therefore, making use of the prior knowledge of the RVFW shape, a carefully interpretation of this delay must be done.

In LBBB, a delay in the activation of the LV with respect to the RV was recognized, whereas in healthy subjects the activation of the LV occurred first.
7.1 Future work

Although the method proposed provides good results for the study of the RV regional wall behavior, there are opportunities for an extension of this work. Possible additions to the current method are explained in the following lines.

First, a change in the thresholding method selected could be able to achieve more accurate results. During the development of the present method, several techniques were tested. The Otsu threshold was selected because it provided better results. Nowadays, many thresholding techniques are available [23] and could be tested in order to find the most accurate one.

In the present method, the selection of the LV center as reference makes this study sensitive to the RV’s changes of shape. Therefore, a change in the coordinate system used to edge detection could provide a most robust wall motion analysis helping to overcome this limitation.

Finally, the development of a new tool able to detect and delete the papillary muscles is also necessary to improve the results. For this task, the use of filtering or binary morphology [24] is suggested. Nevertheless, during the development of the method, morphology and filtering were also tested being very difficult to apply due to the thinness of the RV.
8 References


9 Appendix A: Left Ventricle segmentation

The method used to obtain the RV segmentation was tested to obtain the LV segmentation.

First, a ROI that includes both the ventricles is calculated. In order to perform this ROI the algorithm described in section 3.1 is used. An edge detector is then used to obtain the LV edge point. This edge detection is realized in radial lines (0 to 360 degrees, in steps of 2 degrees) centered in the LV center.

Finally, the regularization of these points is performed using the shortest path algorithm. In this case, the start points used to detect the LV endocardial wall are the set of first points detected. After the application of the shortest path algorithm, a spatial and temporal low pass filtering is performed.

In Fig. 39 the outcome of the proposed method is showed.

![Figure 39](image)

**Figure 39** The contour detection of the LV endocardial wall is shown.

Ten subjects are selected to prove the accuracy of this method. Five frames of different moments of the cardiac cycle are also randomly selected. The automatic and the manual contour detection are then performed.

The results obtained are showed in the following pictures.

Fig. 40 shows the correlation between the manual and the automatic. The correlation coefficient is 0.993.
Spatio-temporal assessment of right ventricle dyssynchronicity by magnetic resonance short-axis cine-loop segmentation

Figure 40: Automatic versus manual areas measured in number of pixels.

The comparison between manual and automatic contour detection is also shown by the Bland-Altman plot in Fig.41. The percentage of the difference between manual and automatic segmentation is 5.1% with a positive standard deviation of 5.4%.

Figure 41: Bland-Altman plot of the area estimates by automatic and manual contour detection
Finally, Fig.42 shows the percentage of area error. This area error was calculated computing the XOR between the manual and the automatic segmentation. The result displays a mean area error of 8.8% with a deviation standard of 2.9%.

Figure 42: The histogram of the percent area error between automatic and manual measurements for 50 MRI images
10 Appendix B: Thresholding based on septum features

Thresholding based on IVS features uses the difference between the IVS wall gray intensity and LV cavity in order to choose the proper threshold for RV segmentation. Edge detection is applied along the rays centered in the middle of the LV cavity. The edge detection is based on the first derivative. Fig.43 shows the gray level of the IVS in the middle. Fig.44 shows the output of the first derivative edge detector. The valley and the peak correspond to the edges of the IVS.

**Figure 43:** The figure shows the intensity gray levels of the IVS (in the middle) and the RV and LV cavities in both sides.

**Figure 44:** The figure shows the outcome to apply the first derivative to the values of Figure 16.
After locating the IVS, the average between the gray value of the IVS and the gray value of the LV cavity is calculated. This value corresponds to the adopted threshold. The process is repeated for all the radial lines that the region of interest contains. After calculating all the partial thresholds, the threshold with the highest value is chosen.

After comparing the results obtained with both thresholds, the Otsu threshold was chosen. IVS threshold could fail due to the smooth variation of tissue intensity between septum and the LV cavity. The detected edges were not enough accurate and the threshold was less stable than the Otsu threshold.
11 Appendix C: Shortest path algorithm flowchart

Figure 45: Shortest path algorithm flowchart.
12 List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AV</td>
<td>Atrioventricular</td>
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<tr>
<td>ECG</td>
<td>Echocardiography</td>
</tr>
<tr>
<td>IV</td>
<td>Intraventricular</td>
</tr>
<tr>
<td>IVS</td>
<td>Interventricular Septum</td>
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<tr>
<td>LBBB</td>
<td>Left bundle branch block</td>
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<tr>
<td>LA</td>
<td>Left atrium</td>
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<td>LV</td>
<td>Left Ventricle</td>
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<td>LVFW</td>
<td>Left ventricle free wall</td>
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<tr>
<td>LVS</td>
<td>Left Ventricle Septum</td>
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<tr>
<td>LVSW</td>
<td>Left ventricle septum wall</td>
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<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
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<tr>
<td>NMR</td>
<td>Nuclear Magnetic Resonance</td>
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<tr>
<td>RA</td>
<td>Right Atrium</td>
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<tr>
<td>ROI</td>
<td>Region of interest</td>
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<tr>
<td>RVFA</td>
<td>Right ventricle free wall</td>
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<tr>
<td>RV</td>
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<td>SA</td>
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Spatio-temporal assessment of right ventricle dyssynchronicity by magnetic resonance short-axis cine-loop segmentation