Characterization of Heart Dynamics in Echocardiography

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To my parents and sister, who through this journey
Across the universe have been my motive, support and Help.
Concluding this project has not been easy, but with effort and
With a little help from my friends, it is Getting better.
Thank you all, now and ever.
With love From me to you.

To my *gold standard*, this is the beginning of a journey.
Thank you for being Here, There and Everywhere.

Acknowledgments

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Abstract

Characterization of Heart Dynamics in Echocardiography

Cardiovascular diseases are the leading cause of death worldwide. In 2019, it was estimated that 32 % of all deaths globally were due to this cause. This happens at national level, according to the colombian National Institute of Health (Instituto Nacional de Salud de Colombia - INS), this is the first cause of death with a 23.5 % of all deaths in the country. In order to diagnose the cardiovascular disease, the echocardiography images are the first choice. This technique allows to evaluate the cardiac structures and its function in most of clinical environments. Echocardiography imaging has several modalities that by taking advantage of key principles of ultrasound, as Doppler imaging and speckle tracking techniques, allows to assess the blood flow in key points, as well as the motion of the cardiac muscle. Besides the different imaging techniques, from echocardiography, it is possible to obtain different measurements to perform a complete assessment: ventricular walls thickness, cardiac chamber dimensions, ventricular volumes, blood flow velocities and ejection fraction. Nevertheless, this techniques are devised to observe muscular and blood features separately.

Given these reasons and remembering that the cardiac function is dependant on interactions between tissues of different characteristics (blood and muscle), This work aims to explore the cardiac function in terms of the dynamic interaction between these tissues, since it may provide complementary information to the current cardiac indicators.

Keywords: Cardiac dynamic, echocardiography, cardiac function, cardiovascular diseases, ultrasound images.

Resumen

Caracterización de la Dinámica Cardíaca en Ecocardiografía

Las enfermedades cardiovasculares son la principal causa de muerte a nivel mundial. Para el 2019, se estimó que el 32 % de todas las muertes a nivel mundial se dieron por esta causa. Este fenómeno se repite a nivel nacional, de acuerdo al Instituto Nacional de Salud, es la principal causa de muerte con un 23.5 % de las muertes en el país. Para su diagnóstico, las imagenes ecocardiografía son la primer elección. La técnica permite evaluar las estructuras cardíacas y su función en la mayoría de ambientes clínicos. La ecocardiografía cuenta con diferentes modalidades que tomando ventaja de principios claves de ultrasonido permiten obtener modalidades como el análisis Doppler y técnicas de rastreo de patrones speckle, permitiendo a su vez evaluar el flujo de la sangre en puntos clave, así como el movimiento del músculo cardíaco. Además de los diferentes modos de imagen, de la ecografía se pueden obtener diferentes medidas para una evaluación completa: grosor de las paredes ventriculares, dimensiones de la cámara cardíaca, volúmenes de los ventrículos, velocidades de flujo y fracciones de eyección. Sin embargo, estas técnicas están dirigidas a ver las características de la sangre y del músculo por separado.

Dadas estas razones y recordando que la función cardíaca es dependiente de interacciones entre tejidos de diferentes características (sangre y músculo), así como de la construcción misma del ventrículo (que explica varios elementos del movimiento cardíaco). Este trabajo propone explorar la evaluación de la función cardíaca en términos de la interacción dinámica entre estos tejidos, pues puede aportar información complementaria a los indicadores de evaluación actuales.

Keywords: Dinámica cardíaca, ecocardiografía, función cardíaca, enfermedades cardiovasculares, imágenes de ultrasonido.

Contents

1 Introduction

Cardiovascular Diseases (CVDs) are the leading cause of death globally. By 2019, an estimated of 17.9 million people died from CVDs, representing the 32 % of all global deaths. Of these deaths, 85 % were due to heart attack and stroke. Over three quarters of CVD deaths take place in low and middle-income countries. In Colombia, according to the INS (*Instituto Nacional de Salud de Colombia*) the main cause of diseases in the country are CVDs, with a 23.5 % of the total number of deaths in the country [1, 2].

In a wider view, CVDs are expressed as cardiac function (CF) impairments [3], that is to say, a CVD affects directly the ability of the heart to meet the metabolic demands of the body, being this the delivery of needed oxygenated blood to remove accumulated cellular waste products [4]. The CF depends on two different tissues: blood and muscle, as demostrated by Torrent-Guasp [5], the heart comprises a mechanism that involves a deeper relation between these the two tissues, that is beyond of the previously known liquid-pump relation, in other words, this complex interaction is summarized as the blood being a leverage for the muscle in its contractile function [6], meaning that a complete CF evaluation must take into account this kind of relations.

Nowadays, the CF evaluation is done by means of the echocardiography imaging (echo) [7], a technique capable of evaluating cardiac structure and function in most clinical environments given the fact that echo does not produces distress to the patient, the information is acquired in real time, does not exposes the patient to ionizing radiation and is cost effective. Among the advantages of echo it is worth to mention some of its image modalities as Doppler Imaging and speckle tracking tools, these techniques allow to characterize some of the cardiac blood and muscle motion [8]. Independent of the echo imaging modality, different cardiac measurements may be used to assess the cardiac function, for example, the Left Ventricle (LV) wall thickness, chamber dimensions, LV chamber volume, flow velocities and the Ejection Fraction (EF) [9], that assesses the percentage of blood volume ejected in each cardiac cycle [10]. However, regardless of the imaging technique, echo is dependant on the operator abilities as well as the clinical personnel behind the interpretation of the acquired data [11], besides, literature has demonstrated that measurements as the EF is not accurate and is even preserved in case of cardiac failure [12, 13].

As an addition and linking with the previously stated, the mentioned measurements and imaging techniques are used in clinical environments to analyze muscular features and blood features separately leaving aside the briefly described system of leverages involved in the cardiac function [5], which structurally does not exist and which probably is the role of the blood during the cardiac cycle [14]. In other words, if any change in this leverage system between the cardiac tissues (muscle and blood) is present, it would be reflected in variations of volume and geometry, this as a consequence of contractility alterations [15, 16, 17]. In this context, this work aims to combine information from the blood and muscular features, showing new approaches on the characterization of cardiovascular diseases. Regarding the subject of this work, different strategies have been proposed in literature devoted to analyze these features separately.

To begin, it is worth to mention that at the blood features field this analysis is performed by observing the motion of blood inside the ventricular chambers, usually by means of speckle tracking techniques [18] and echodynamography [19]. The first work, as proposed by [18], titled *Blood Speckle-Tracking Based on High-Frame Rate Ultrasound Imaging in Pedriatric Cardiology*, the feasibility, accuracy, and potential clinical applications of using blood speckle-tracking techniques, based on high-frame rate ultrasound imaging in pediatric patients is determined. To do so, the method is validated with 102 subjects divided in 51 control cases (ranging from 2-day-old to 10-year-old children), 47 cardiac patients (ages ranging from 1 day to 11.5 years) and four healthy fetuses (21, 24, 29 and 29 weeks of age). The blood speckle-tracking is a technique based on high-frame rate images tracking to measure and visualize blood vector velocity fields. According to the reported by the authors, the method is feasible in clinical environments, as it is capable of measure the intraventricular blood flow and to relate the information with certain clinical conditions. Compared to color Doppler imaging, this method is capable of obtaining information from different directions, given the fact that Doppler is only capable of obtaining information from the main direction of the ultrasound beam.

Secondly, the work by Oktamuliani, et al [19], with the title *Left Ventricular Vortices in Myocardial Infarction Observed with Echodynamography*, managed to quantify the vortex formation and flow situation by means of an adimensional analysis based on the numerical solution of the Navier-Stokes equations. In order to do so, nine cases (six healthy and six with myocardial infarction) of color Doppler echocardiography were processed with a echodynamography (that is a method to deduce two-dimensional blood flow vectors from conventional color Doppler ultrasound images by considering that the blood flow is divided into vortex and base flow components), and then compared to find-out differences between healthy and diseased cases. The study showed that the transmitral velocity was faster in infarcted cases than that of healthy cases. As for the vortex formation, in the case of infarcted cases, the vortex direction was irregular when compared to control cases. The vortex index, as well

as the vortex equivalent diameters and Reynolds number were significantly greater in the infarcted cases than in healthy cases. Some interesting observations were exposed by the authors as, the Reynolds number increased with the vortex size, the Reynolds number also increased when more turbulent flows were found, the results of this study indicate that the generation of disturbed flow may generate energy loss, evidencing impaired cardiac function.

The cardiac function analysis is also approached by observing the muscluar feature analysis, this is principally performed by quantifying the motion as seen in [20, 21] and by characterizing the muscular strain [22, 15]. In order to elaborate, in the work titled *Cardiac MRI demonstrates compressibility in healthy myocardium but not in myocardium with reduced ejection fraction* by Kumar, et al [22], it aims to determine if the myocardial volume in systole is equal to the volume in diastole in healthy myocardium using MRI (Magnetic Resonance Imaging) images and transthoracic echocardiography, this work also aims to determine whether there are similar myocardial volume changes in cases with heart failure with reduced ejection fraction (HFrEF). In order to do so, the acquired MRI images were processed using classic methods of volumes computation as Simpson's disk summation using short axis cine images of the left ventricle, for the echocardiography images, the volumes were computed with linear measurements utilizing the parasternal long axis imaging plane, from this work the authors concluded that the healthy myocardium is compressible and unhealthy myocardium (as the case with HFrEF) is not.

In that line, the paper *Characterization of motion patterns by a spatio-temporal saliency descriptor in cardiac cine MRI* written by Atehortua, et al [20] a characterization of the regional cardiac motion patterns in cMRI (Cine Magnetic Resonance Imaging) based on a spatio-temporal saliency descriptor is proposed, for this case, the cardiac cine images were processed with a multiorientated and multiscale approach that highlights changes, then these changes were followed across time in order to obtain a spatio-temporal saliency map. Later, with these maps a saliency dispersion is computed at clinically relevant cardiac locations as a measure of motion patterns in order to discriminate between control and subjects with hypertrophic cardiomyopathy, this work manages to relate motion abnormalities in the apical, anterior, basal and inferior segments revealed by the saliency dispersion with hypertrophic cardiomyopathy and control subjects during the systolic and diastolic phases. A work introduced by Chumarnaya, et al [15], *Left Ventricle Functional Geometry in Cardiac Pathology*, presents a methodology to characterize the change of the ventricular shape during contraction and relaxation stages. As a result, the work reveals differences in the change of shape between control, dilated (dilated cardiomyopathy) and ischemic cases.

Finally, at the muscular feature analysis, a work presented by Parages, et al [21], titled *Estimation of Left Ventricular Motion from Cardiac Gated Tagged MRI Using an Image-Matching Deformable Mesh Model*, a strategy based on a deformable mesh model that con-

sists in a model that manages to adapt its shape to the anatomical structure of the myocardium from the segmentation of inner and outer left ventricle walls at the end of diastole frame is proposed. This work is tested with control, hypertensive and mitral regurgitation patients, in order to estimate a motion field that manages to represent motion differences between these three kind of cases. The method is validated using tagged MRI images from 27 patients divided into cases with no pathology, hypertension and mitral regurgitation. A measure of the displacement error is computed to test the proposed estimation using the non-pathological cases only, this is determined by comparing the tracking of a gold-standard set of points (landmarks) and the tracking of the points computed by the deformable mesh model proposal, the obtained results are reported for the basal, mid and apical regions from short-axis images, obtaining results of $0{,}96 \pm 0{,}02, 0{,}85 \pm 0{,}1, 0{,}98 \pm 0{,}4$ for each region, respectively, which according to the authors is quite accurate when compared to the gold-standard landmark tracing.

The cited works, show results that are opening new paths in the characterization of the cardiac function, evidencing that the this parameter is governed by more complex mechanisms [23]. From this, the concept of cardiac function is introduced as the result of the leverage-interaction mechanism between the blood and muscular tissues [5], describing nonlinear interactions of the cardiac muscle function and variations of volume and geometry, that as a consequence, are reflected as changes in pressure and flow patterns by alterations in contractility and relaxation stages [16, 15].

1.1. Contribution and Academic Products

The cardiac dynamics is a balance between the properties of the cardiac muscle and the blood tissue, that is to say, the cardiac function is dependant on the relation of these two tissues [24, 25, 6]. The characterization of the cardiac function is devoted to observe muscular and blood features separately [26, 27], therefore an exploration of the dynamic patterns in the left ventricular chamber is proposed in order to provide a new insight on complementary information to the current cardiac indicators [28, 29]. The presented work is divided in two main contributions:

- A filtering technique that removes speckle noise from echocardiograhpy images in large areas while preserving key cardiac structures, it consists in a bank of multi-scale and multi-orientation filters that captures anisotropic information.
- A novel strategy to characterize the cardiac dynamics of the left ventricular chamber was explored, this approach manages to highlight different patterns in cases with infarction in a velocity-acceleration plane in a single cardiac cycle.

Academic products

The contributions of this work as well as their results were published in:

- **Jorge Daniel Jara-Hurtado**, Álvaro Andrés Sandino, Angélica Atehortúa, Carlos Alberto Ortíz Dávila and Eduardo Romero. *Speckle Noise Reduction in Echocardiography Using a Bank of Filters Based on Oriented Structuring Elements.* Proceedings of the 15th International Seminar on Medical Information Processing and Analysis SIPAIM 2019, Medellín (Colombia), November 2019.
- **Daniel Jara-Hurtado**, Álvaro Andrés Sandino, Andrés Felipe Carrera-Pinzón, Carlos Alberto Ortíz Dávila and Eduardo Romero. *Exploring the Left Ventricular Chamber Dynamics in Echocardiography Images.* Proceedings of the 17th International Seminar on Medical Information Processing and Analysis SIPAIM 2021, Campinas (Brazil), November 2021.

1.2. Thesis outline

The remaining chapters of this work are organized as follows:

- ***Chapter 2: Speckle noise reduction in echocardiography using a bank of filters based on structuring elements***. This section introduces a novel speckle noise filtering strategy implementing a bank of filters that captures anisotropic information and additionally preserves cardiac structures. In order to do so, a bank of filters based on morphological operators that vary their size and orientations, that is to say by applying a multi-scale and multi-orientation approach, is implemented aiming to capture information from different scales and angles.
- ***Chapter 3: Exploring the left ventricle chamber dynamics in echocardiography images***. The third chapter presents an exploratory work on the analysis of the left ventricular chamber dynamics from ultrasound 2D videos. This exploration is based on a motion analysis from a vector field devised from a regional tracking approach. By testing in two different conditions (non-infarcted vs infarcted cases), this exploration manages to highlight different patterns in infarcted cases.
- ***Chapter 4: Conclusions and perspectives***. The closing and final section presents the conclusions of this work, as well as the achieved contributions and the impact in the research area. Additionally, some future work and new research horizons projected by this thesis are also mentioned.

2 Speckle Noise Reduction in Echocardiography Using a Bank of Filters Based on Structuring Elements

This section introduces a filtering strategy to improve the visualization of cardiac structures in echocardiography images affected by speckle noise. In order to do so, a technique based on morphological operations as well as a multi-scale and multi-orientated analysis is devised to obtain several versions of a filtered image, then by pixel-wise operations an averaged and filtered image is obtained. The presented strategy is capable of preserving most of the important and delicate cardiac structures as the base of the left ventricle and the apex area, besides it manages to remove most of the noise from the left ventricle cavity, facilitating manual and automatic segmentation of this area.

2.1. Introduction

Echocardiography is the most commonly used heart imaging technique due to a lot of advantages, namely: is a non-invasive procedure, portability, gives precise information about the cardiac function, allows complete heart visualization, and it has temporal spatial resolution. Nevertheless, echocardiography has some considerable limitations, like imaging artifacts, speckle noise and low contrast due to acoustics conditions in the body of the patient. These problems may hamper the capability of the physician to take accurate decisions. Therefore, the more relevant information that can be preserved from an ultrasound image, the easier it is to make decisions about the treatment plan [30].

Lots of image quality improvement methods have been proposed, these methods rely on different filtering strategies like: anisotropic diffusion filtering [31, 32, 33], non-local means filtering [34, 35], combinations of linear and non-linear filters [30], wavelet decomposition [36], morphological operations [37], multi-direction median filtering [38], to name some of them. Though those methods manage to get some interesting results, they have some issues, i.e., even when speckle is reduced not so much is gained in the diagnosis terrain [31, 39, 30], not all the information from the images is taken into account [34, 40], the computational cost is high [39], among others.

In this proposal a comparison against some of the previously mentioned filters is made, those filters are: the anisotropic diffusion filter as proposed by Ramos-Llordén et. al[32],

which includes a probabilistic-driven memory mechanism, that according to the authors it overcomes the over-filtering problem in critical cardiac structures, but it requieres a priori knowledge of the images. Other is a non-local means filter, by Buades et. al[35] this technique is based on non-local averaging of all pixels in the image to remove noise instead of averaging local neighborhoods of pixels, this is translated in better image clarity after filtering. Finally, a detail preserving anisotropic filter that is based on the methods proposed by Aja-Fernández et al.[33] and Yu et al.[41] which consists in an anisotropic diffusion filter with an estimation of the variation coefficient of both signal and noise itself.

After decades of investigation, most of the speckle noise filters degrade the cardiac structures. A main contribution of this work is a filtering technique that removes speckle noise, while highly preserving the cardiac structures in 3D echocardiography imaging. This operator consists of a bank of morphological multi-scale filters that sweeps the image with different preferred orientations, that is to say, that anisotropically capture information following different angles. The method starts by dilating the input image with a basic ellipsoid element placed at different directions, typically every 5°. The different outputs are averaged as a representant of a particular scale. The structural element size is then varied to obtain different scale analyses and each of this elements is dilated with the image as described. The set of outputs from each of the scales is also averaged, being this the final filtered image.

2.2. Methodology

The proposed filtering method consists in implementing a bank of morphological operators by using a dilation operator, aiming to enlarge bright regions surrounded by dark regions and to shrink dark regions surrounded by bright regions, besides, this operator is preferred given the fact that it preserves and highlights subtle and small regions, which are of clinical interest. The speckle noise, which can be though of as small dark spots, will be removed, and structures which can be seen as bright spots, will become larger.

2.2.1. Extraction of Region of Interest (RoI)

As a first step an echocardiography Region of Interest (RoI) was extracted by a simple thresholding, as shown in Figure **3-6**.b. The resultant region is divided in a set of orientations $\Delta\theta$ from ϕ_2 to ϕ_1, every 5°.

2.2.2. The bank of single scale filters

This bank aims to conserve relevant information in the space of frequency and it works by combining a series of low pass filters since the effect is more observed at places where the intensity changes rapidly, while uniform regions remain alike, except at their edges. For so

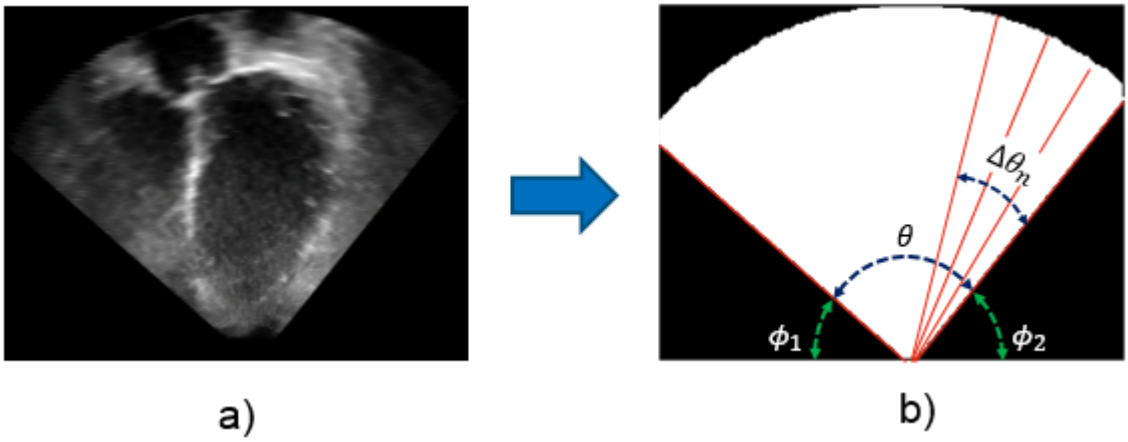

Figure 2-1: a) Original echocardiography image (coronal view) b) Angles ($\Delta\theta$) taken from RoI.

doing, the gray level image is dilated by an oriented elliptic-shape structuring element, with major and minor axes (a, b), as referred in equation 2-1.

$$I_\theta(i,j) = I_o(i,j) \oplus SE_{\theta,a,b}; \quad \Delta\theta \in \{\theta_1, ..., \theta_n\} \tag{2-1}$$

Being I_o the input image, $I_{\theta(i,j)}$ the filtered image in the θ angle of the elliptical structural element (SE) and n the number of orientations. The major axis length varies between a third and a fourth of the largest dimension of the image. This process is repeated for each of the $\Delta\theta$ orientations as shown in figure **2-2**. Afterwards, a representative low pass image is obtained as from the average of all filtered images, as illustrated in figure **2-2**. Finally, a pixel to pixel product between the input image and the representative low pass image is performed to obtain a final filtered image. This step is similar to a binary AND operator, but instead of obtaining a one-outcome, the product of the two inputs is taken, conserving the palette of gray levels, in this case the ventricular left chamber, as illustrated in Figure **2-2**.

2.2.3. Multi-scale Bank of Filters

A multi-scale approach fuses information of several banks of filters, each defined by changing the size of the structural element. Afterwards, an average of the multi-scale filtered images is performed to obtain the final filtered image, as shown in Figure **2-3**.

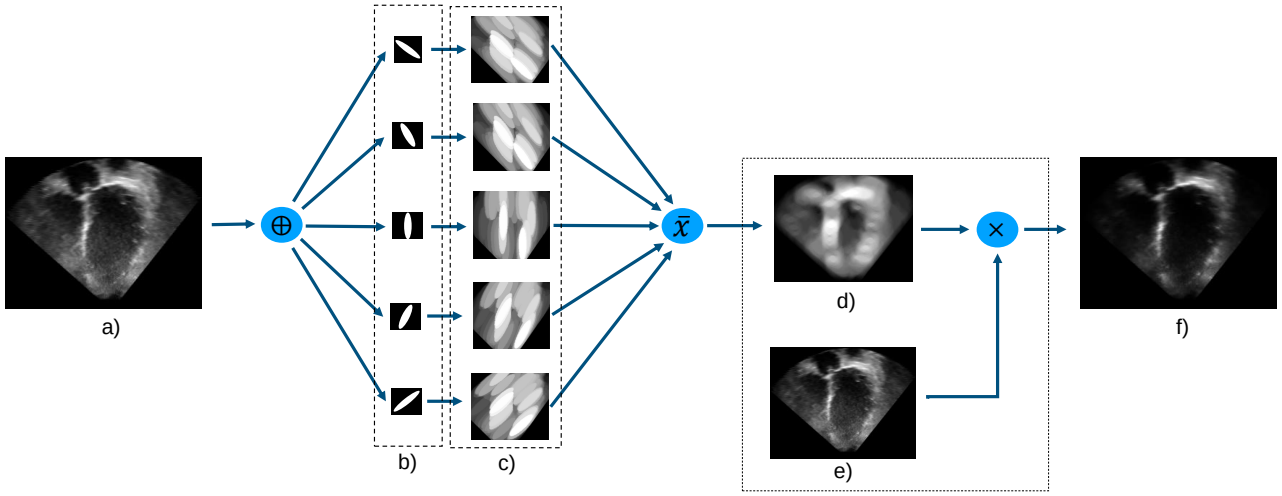

Figure 2-2: a) Original echocardiography image, b) Some rotations of the Structuring Element (SE): $150°, 120°, 90°, 60°, 30°$, c) The resulting image dilation for each rotation, d) The average dilation image, f) the filtered image, obtained with a multiplication between images a and d.

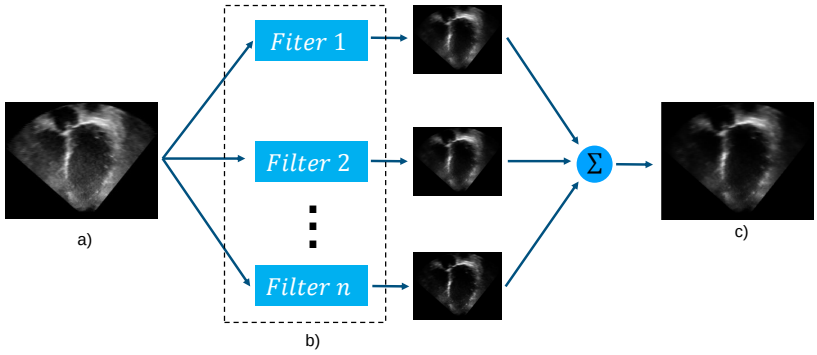

Figure 2-3: Final implementation of the Multi-Scale Bank of Filters approach, from left to right: an input image, the filtered image in different scales sum, the output image after filtering.

2.3. Evaluation and Results

2.3.1. Database

The proposed approach was tested using 10 echocardiography cases in the apical view, randomly extracted, from the Challenge in Endocardial Three-dimensional Ultrasound Segmentation (CETUS) at MICCAI Challenge, held in 2014 [42]. This database consists of 45 cases divided as follows: 15 healthy patients, 15 patients with previous myocardial infarction, 15 patients with dilated cardiomyopathy, involving three different machines, namely: a GE Vivid E9 with a 4V probe, a Philips iE33 with a X5-1 probe and a Siemens SC2000 with a 4Z1c probe. The quantity of frames between cases is variable, having as minimum 15 frames per cardiac cycle and a maximum of 47 frames per cardiac cycle.

2.3.2. Qualitative interpretation

Figure **2-4** shows three different cases (rows) with the filtered images by either the proposed method or related works (columns), namely from left to right: Anisotropic Diffusion Filter (ADMSS) [32], Non-Local Means Filter (NLMF) [43], and Detail Preserving Anisotropic Filter (DPAD) [33], being the first column the noisy image. Notice how the presented method achieves to reduce the noise in the image, while the important information is preserved, as observed by the expert cardiologist co-authoring this publication. The images evidenced a loss of the endocardial border related with trabeculaes. However, the myocardium wall is preserved so that it could be objectively measured and its contractility function assessed, as also discussed by our expert.

dThe proposed method achieves a good performance that is similar to the ADMSS filter, with the advantage of cleaning the blood pool noise and also the noise in the window field by preserving the myocardium wall. In the expert cardiologist opinion, the image obtained from the DPAD filter had not change after it was processed. Finally, the worst result was obtained by the NLM Filter, because this filter softens out the edges and in consequence, the myocardium contractility can be erroneously assessed by an expert because of the false endocardial borders.

A side advantage with this proposal is that it does not require a parameter tuning to obtain good results, unlike the ADMSS filter, which relies on the adjustment of its parameters to obtain good quality filtered images, i.e., relevant structures such as the myocardium are preserved while the noise is removed.

2.3.3. Quantitative Results

The quantitative performance of the filter was evaluated following the strategy proposed by Biradar et. al [44], which consisted in contaminating the input images with speckle noise at a variance of 0.1 followed by filtering these noisy images with each method. The filtered

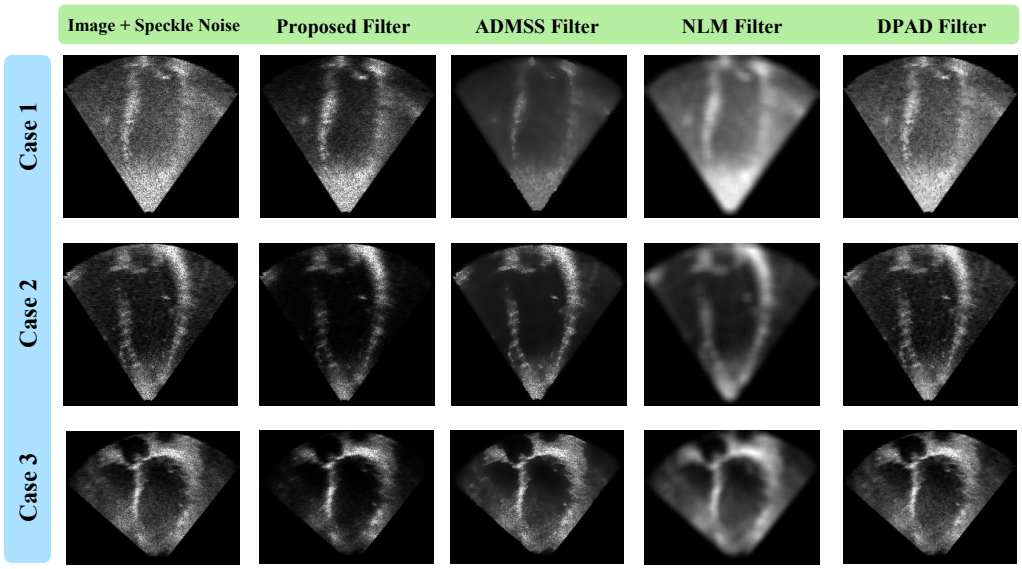

Figure 2-4: Filtering methods. From left to right: input images with speckle noise, filtered image with the proposed method, ADMSS filtering, NLM filter and DPAD filter.

image was contrasted against the input image, as follows: first, a myocardium segmentation was performed by an observer in all images, original and filtered, aiming to define the cardiac structures in the filtered image. Afterwards, a measurement of entropy inside the left ventricle blood pool was computed for each filtered image. This is an important task to automatically delineate the endocardial cavity in several segmentation approaches. Table **2-1** shows the obtained average Dice score and Hausdorff distance and its standard deviation in parenthesis. The proposed method outperforms other state-of-the-art methods: Anisotropic Diffusion Filter (ADMSS) [32], Non-Local Means Filter (NLMF) [43], and Detail Preserving Anisotropic Filter (DPAD) [33].

The results show that the proposed filter gets the best performance, demonstrating this filter is capable of preserving relevant cardiac structures and objectively measure the contractibility of the myocardial wall.

Proposed		**ADMSS**		**NLMF**		**DPAD**	
Dice Score	**Hausdorff Distance**	**Dice Score**	**Hausdorff Distance**	**Dice Score**	**Hausdorff Distance**	**Dice Score**	**Hausdorff Distance**
0,84 (0,05)	**4,98 (1,04)**	0,82 (0,04)	5,22 (0,91)	0,81 (0,03)	5,30 (0,83)	0,81 (0,05)	5,28 (1,44)

Table 2-1: Mean and standard deviation of myocardium segmentation made over the images obtained from the different filtering methods.

Table **2-2** shows the average and standard deviation of the entropies inside the left ventricle blood pool. The result is significantly different ($p < 0,05$) between the proposed filter and the DPAD filter, between the proposed filter and the other filtering methods there not exist statistical significance. The results confirm that entropy measure is slightly smaller for the ADMSS filter.

Proposed	**ADMSS**	**NLMF**	**DPAD**
5,59 (0,84)	**5,46 (0,60)**	6,09 (0,45)	6,57 (0,52)

Table 2-2: Mean and standard deviation of the left ventricle blood pool entropy.

2.4. Conclusions

This research work presented a novel filtering technique that combines mathematical morphology, multi-scale analysis and a customize bank of filters. The filter is capable of conserving most of the important structures, i.e, the base of the left ventricle and the apex area, where most of the filters tend to fail. In addition, it manages to remove most of the noise from the blood pool, a crucial point of start to improve automatic ventricular segmentation strategies. Future work will evaluate the filtering performance in larger data sets.

3 Exploring the Left Ventricle Chamber Dynamics in Echocardiography Images

This chapter presents an exploratory investigation on the estimation of ultrasound blood dynamic patterns within the left ventricular chamber. The followed methodology for this work consisted, as a first step, in segmenting the left ventricular chamber, then, to apply a multi-scale and multi-orientated bank of filters in order to highlight traceable areas, later, to implement a regional tracking across time, in order to find associable patterns with different pathological conditions. The results of this work, are shown as velocity vs. acceleration phase planes and effectively reveal differences in regions of low velocity-acceleration in infarcted cases, these findings are coherent with motion limitations.

3.1. Introduction

Echocardiography is the most widely used cardiovascular imaging modality and is considered the choice for evaluating cardiac structure and function in most clinical conditions[45]. Besides costs, portability and little distress to the patient [46], ultrasound also provides useful measurements of the cardiac structure, namely size and shape of cardiac chambers, valvular regurgitation indices and intracardiac hemodynamics [45, 47]. Classically, ultrasound techniques analyze the motion and deformation of the myocardial muscle by first order approximations, i.e. strain and strain rate [48]. Nevertheless, the cardiac efficiency is the result of a complex not linear interaction of tissues with different physical properties and adaptations. Interestingly, the heart moves as a result of the interaction between the muscle machinery and the blood tissular properties. In fact, the blood condition leverages the muscle capacity and defines most of the muscle function [5], particularly changes in pressure and flow patterns, and variations of volume and geometry by alteration of contractility and relaxation stages [15, 16, 17]. These spatio-temporal patterns have shown differences between control and unhealthy subjects at the level of the muscle [15] and blood motion [49, 18], yet the functional characterization is basically devoted to estimate muscle features [48].

The analysis of the cardiac function is usually devoted to the cardiac muscle, yet the cardiac dynamics is a delicate balance between properties of the cardiac structures and the blood tissue. This investigation explores the possibility of estimating ultrasound blood dynamic patterns of the cardiac left chamber in different pathological conditions. This work

associates a novel characterization of the dynamic patterns within the left ventricular chamber in ultrasound images with different pathological conditions.The method is divided in four essential steps: a manual segmentation of the left ventricular chamber followed by a multi-orientation and multi-scale filtering. Then the processed images are divided in smaller homogeneous regions with a super-pixels algorithm. The regions are then tracked across a cardiac cycle in order to compute a velocity-acceleration phase plane to extract motion features. By testing pathological conditions, this approach highlights very different patterns in patients with infarction.

3.2. Methodology

In this work, the characterization consists in four steps, as shown in Figure **3-1**. To begin with, the detection of the Region of Interest (RoI) is performed by means of a manual segmentation of the left ventricular chamber (Figure **3-1**.A).
Following this a multi-scale and multi-orientated bank of filters is applied, then a super-pixels[50] algorithm is used to compute smaller regions within the left ventricular chamber, the intensities inside each region are averaged (Figure **3-1**.B).
Afterwards, each of these homogeneous regions are tracked by setting the closest region in the next slice with a similar averaged intensity value (Figure **3-1**.C).
Finally velocity and acceleration features are extracted from the performed tracking (Figure **3-1**.D) in order to observe differences between pathological and control subjects.

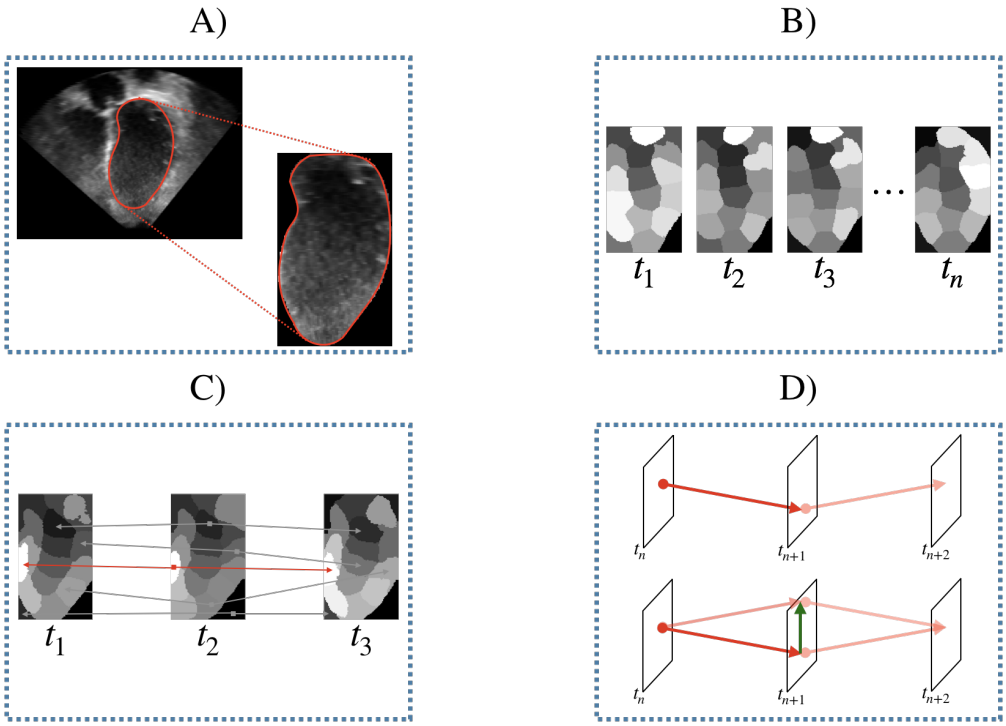

Figure 3-1: Proposed methodology. A) RoI identification from the input image. B) Regional characterization of the left ventricle chamber. C) Region Temporal tracking. D) Feature extraction.

3.2.1. Database

The proposed approach was tested using the mid slice of echocardiography videos in the apical view, from the Challenge in Endocardial Three-dimensional Ultrasound Segmentation (CETUS) at MICCAI Challenge, held in 2014 [42]. This database consists of 45 cases divided as follows: 15 control, 15 patients with previous myocardial infarction, 15 patients with dilated cardiomyopathy, involving three different machines, namely: a GE Vivid E9 with a 4V probe, a Philips iE33 with a X5-1 probe and a Siemens SC2000 with a 4Z1c probe. The number of frames is variable between cases, i.e, having as minimum 15 frames per cardiac cycle and a maximum of 47 frames per cardiac cycle. From this set, two control and two patients with myocardial infarction were selected, checking the cardiac structures were observable.

3.2.2. Detection of Regions of Interest

The ventricular chamber is manually delineated for every frame, as illustrated in Figure **3-2**. After the ventricular chamber is delineated a bounding box that defines the Region of Interest is computed. Nevertheless, it is observed that the ventricular chamber has some slight

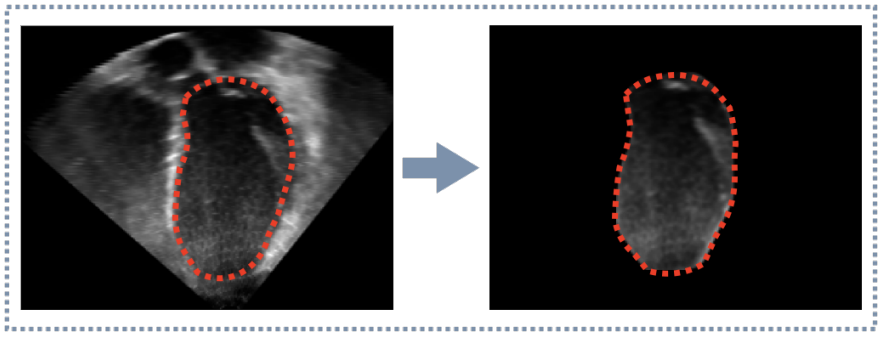

Figure 3-2: Segmentation of the region of interest.

position changes across time that may difficult the characterization process, hence a bounding box that captures these changes is required. In order to do so, each of the segmented frames is binarized (Figure **3-3**.A), then the binarized images are added, obtaining a gray-scale image that contains the position changes across time (Figure **3-3**.B), this image is also binarized as seen in Figure **3-3**.C, finally the bounding box that encloses the position variation for a sequence of image is obtained, as shown in Figure **3-3**.D.

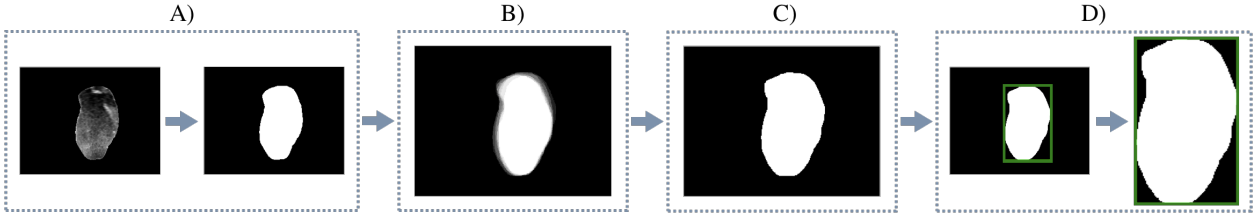

Figure 3-3: Bounding box computation over the segmented image.

3.2.3. Characterization

Multi-Orientation and Multi-Scale Bank of Filters

Every segmented frame is processed by a multi-orientated and multi-scale bank of filters [51]. At each of these stages, an input image is dilated with an elliptical structuring element that varies its orientation and size an as described in Equation 3-1.

$$I_\theta(i,j) = I_o(i,j) \oplus SE_{\theta,a,b}; \quad \Delta\theta \in \{45°, 90°, 135°, 180°\} \tag{3-1}$$

Being I_o the input image, I_θ the filtered image in the θ direction after the described structuring element SE has been applied. The major and minor axis of the structuring element are defined by a, b. The number of scales was set to three, that is to say, the major axis length varies from half to one third to the width of the described bounding box.
The dilation operation is repeated for each of the $\Delta\theta$ orientations, resulting in several versions of filtered images, as illustrated in Figure **3-4**.A. Afterwards, the obtained images are added to obtain an image with the preserved information across orientations and scales, as shown in Figure **3-4**.B.

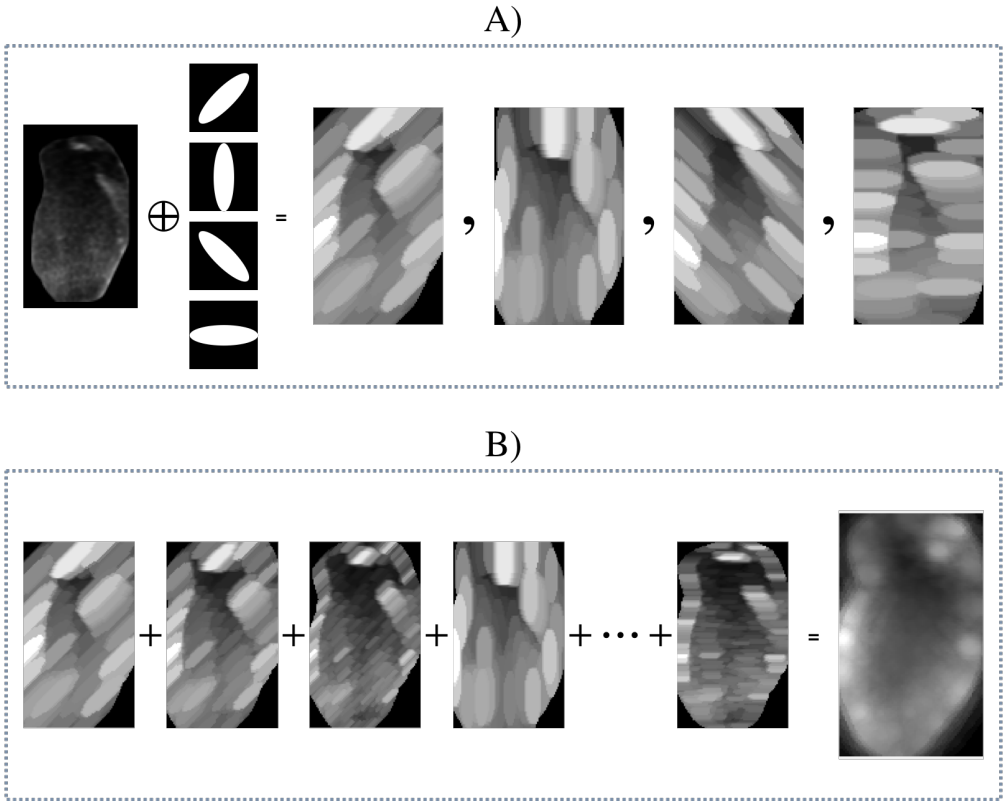

Figure 3-4: Applying a multi-scale and multi-orientation bank of filters. A) Previously defined RoI dilation with structuring element and some results from this operation, B) Integration of the previously dilated versions resulting in an image of the ventricular chamber with preserved information.

Regional Approach

By a super-pixel partition [50], the previously processed images are divided into smaller and more homogeneous regions, Figure **3-5**. Setting the number of regions to thirty (30), to obtain a comparable partition for every frame. This is accomplished by setting the *compactness* parameter of the super-pixel method to 40, since regions were observed as homogeneous from 35. Considering that distribution of intensities at every super-pixel is approximately normal and that textures may not preserve across time given the blood and noise motion, the mean intensity (μ) was used as the region representant, Figure **3-6**.

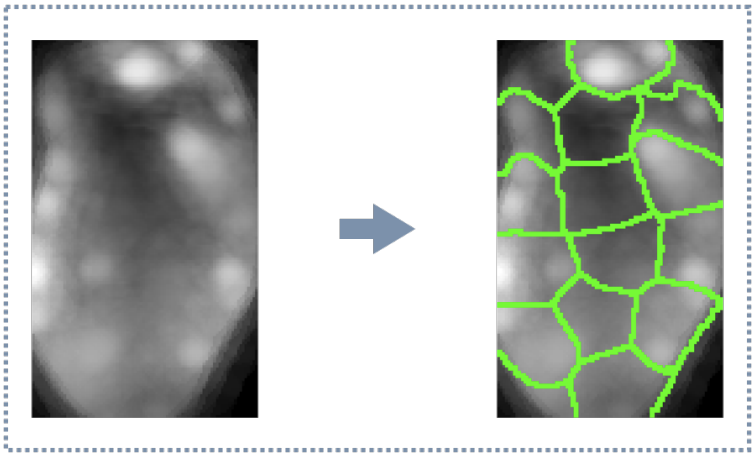

Figure 3-5: Computing regions (super-pixels) in an image of the left ventricular chamber.

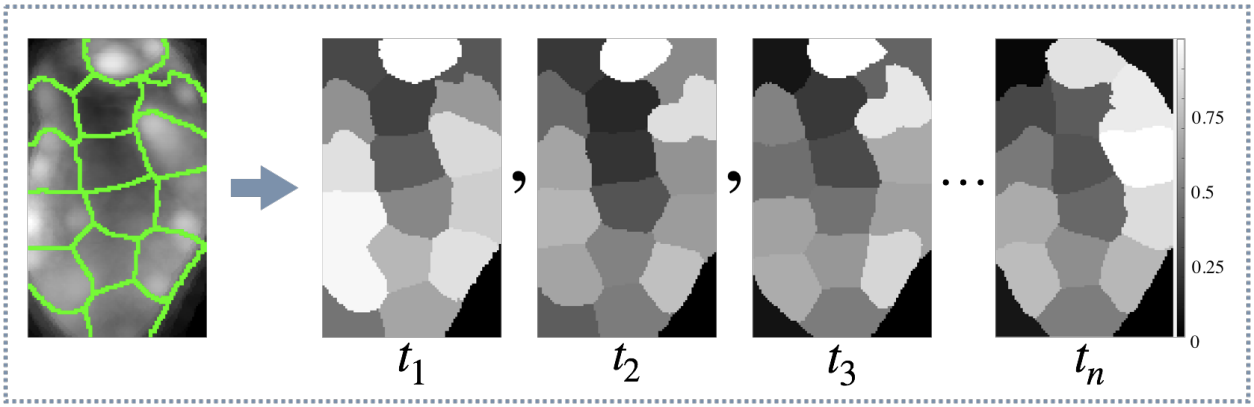

Figure 3-6: Representative value μ computed for every RoI.

3.2.4. Region temporal tracking

This step consists in following every region along the cardiac cycle, as shown in Figure **3-7**, basically tracking the superpixel representant location within its neighborhood in the consecutive time.

The proposed tracking begins by considering the centroid of the previously computed regions and their representant. Tracking takes the intensity value and the centroid coordinates of a super-pixel at the t_n frame and searches for the most similar region or superpixel within the closer neighborhood in the next frame t_{n+1}, as described in Equation 3-2.

$$d_x = min\Big(|\mu_{n+1} - \mu_n| + \sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2} \Big) \tag{3-2}$$

Being μ_n and μ_{n+1} the region representants at frame (n) and $(n+1)$, x_n, y_n and x_{n+1}, y_{n+1}

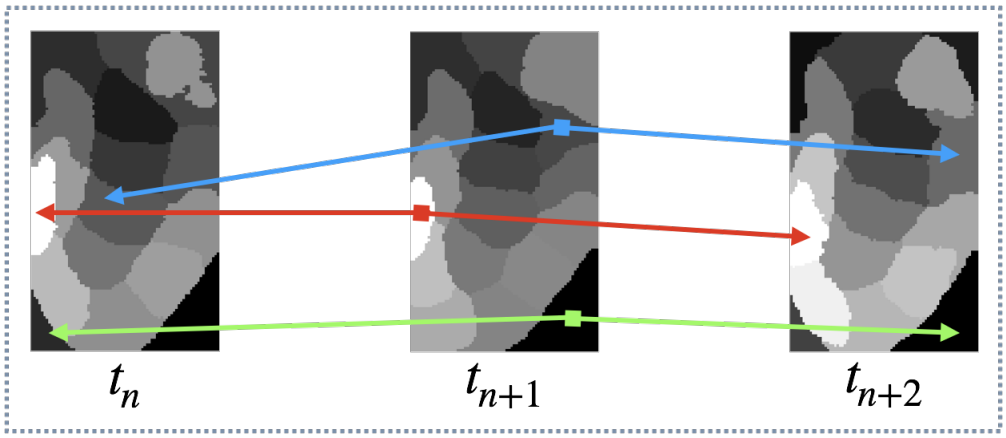

Figure 3-7: Illustrative regional tracking of three regions for three frames of a cardiac cycle.

their centroid region coordinates and d_x the minimum distance between two close and similar regions.

3.2.5. Feature extraction

After regions are tracked, a vector field is obtained along a cardiac cycle. Hence, velocity and accelerations fields are computed. A characterization of the ventricular dynamics is estimated from the velocity-acceleration phase space. The ventricular chamber motion is different from the inner to the outer regions, as illustrated in figure **3-8**: corner and inner areas move very little, while the chamber peripheral regions show high motion patterns.

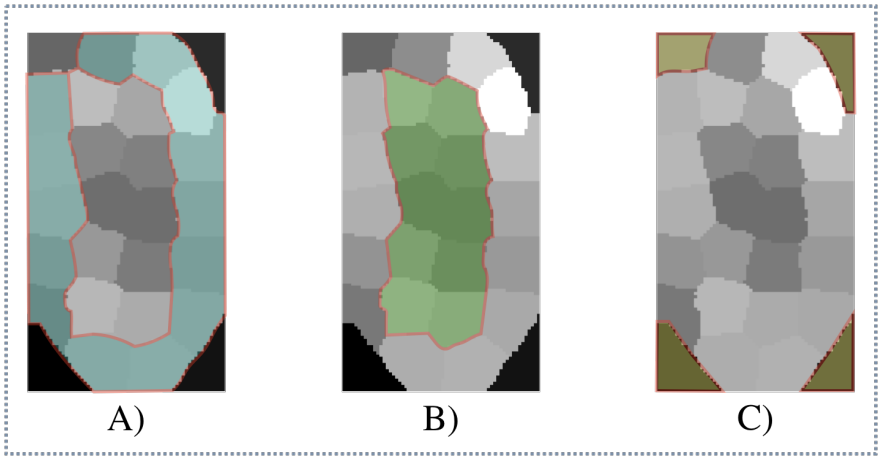

Figure 3-8: Regions inside the Left Ventricular Chamber. A) Peripheral regions. B) Inner regions. C) Corner regions.

Different motion profiles are captured by dividing the velocity field in three intervals, i.e., low, mid and high, an so the acceleration field. These profiles are extracted from the phase plane in three disjoint regions, as illustrated in figure **3-9** and a measure of density is set by counting the number of points per region and dividing by the total number of points, as described in Equation 3-3.

$$P_p = \frac{\text{Points in Region}}{\text{Total Number of Points}} \tag{3-3}$$

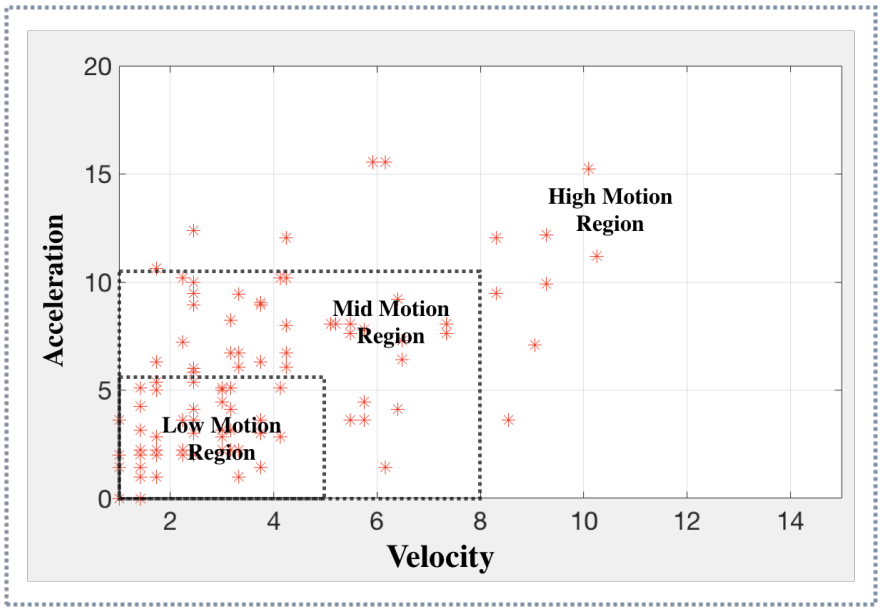

Figure 3-9: Division of phase plane in motion profiles.

3.3. Results

3.3.1. Qualitative evaluation

Figure **3-10** shows three different super-pixels followed along a cardiac cycle from the peripheral, inner and corner region, respectively. The results suggest there are areas with little to no motion (Figure **3-10**.B, D) and areas with high motion (Figure **3-10**.A). Endeavours concentrated then on following these super-pixels, which are basically located close to the ventricular chamber boundary.

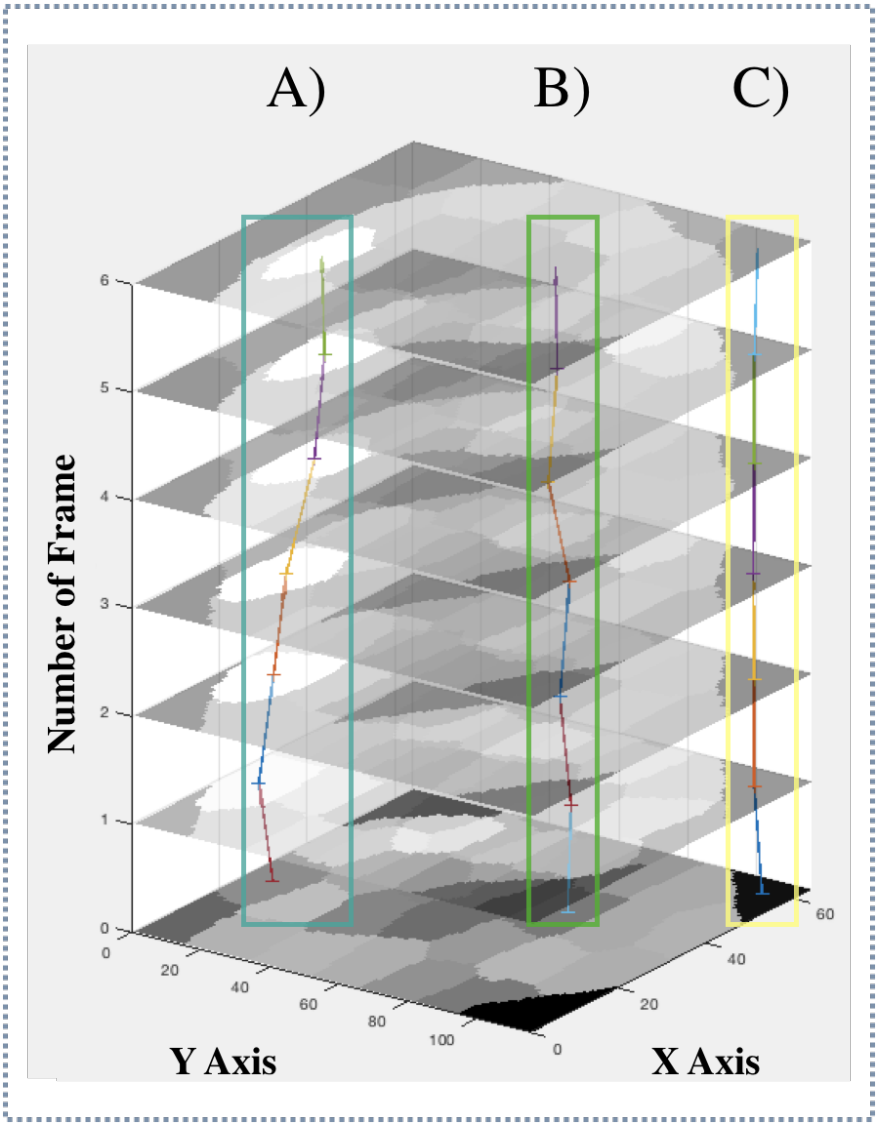

Figure 3-10: Region temporal tracking for three super-pixels: A) Peripheral region. B) Inner region. C) Corner region.

3.3.2. Quantitative results

The different super-pixels were tracked along the cardiac cycle and the velocity-acceleration relation was estimated for those with more motion. The obtained velocity-acceleration for each superpixel and frame was plotted in the velocity-acceleration phase plane. Then a relative region partition is proposed in order to measure the density of points, as illustrated in Figure **3-11**, this consisted in taking the highest value of velocity and acceleration for each subject and use this value to divide the phase plane in three equal parts, resulting in low, mid and high motion regions. Basically, velocity-acceleration points are concentrated in the low motion region for the patients with infarction while control subjects show a more

homogeneous distribution between regions with low and mid motion. Table **3-1** explicitly shows density figures, allowing to observe that motion is concentrated in low region for unhealthy cases. As for control cases, the concentration is evenly, complementing observations from figure **3-11**. These findings correlate with the described for patients with infarction, i.e., lose of motion capabilities by scar formation after ischemic diseases [52].

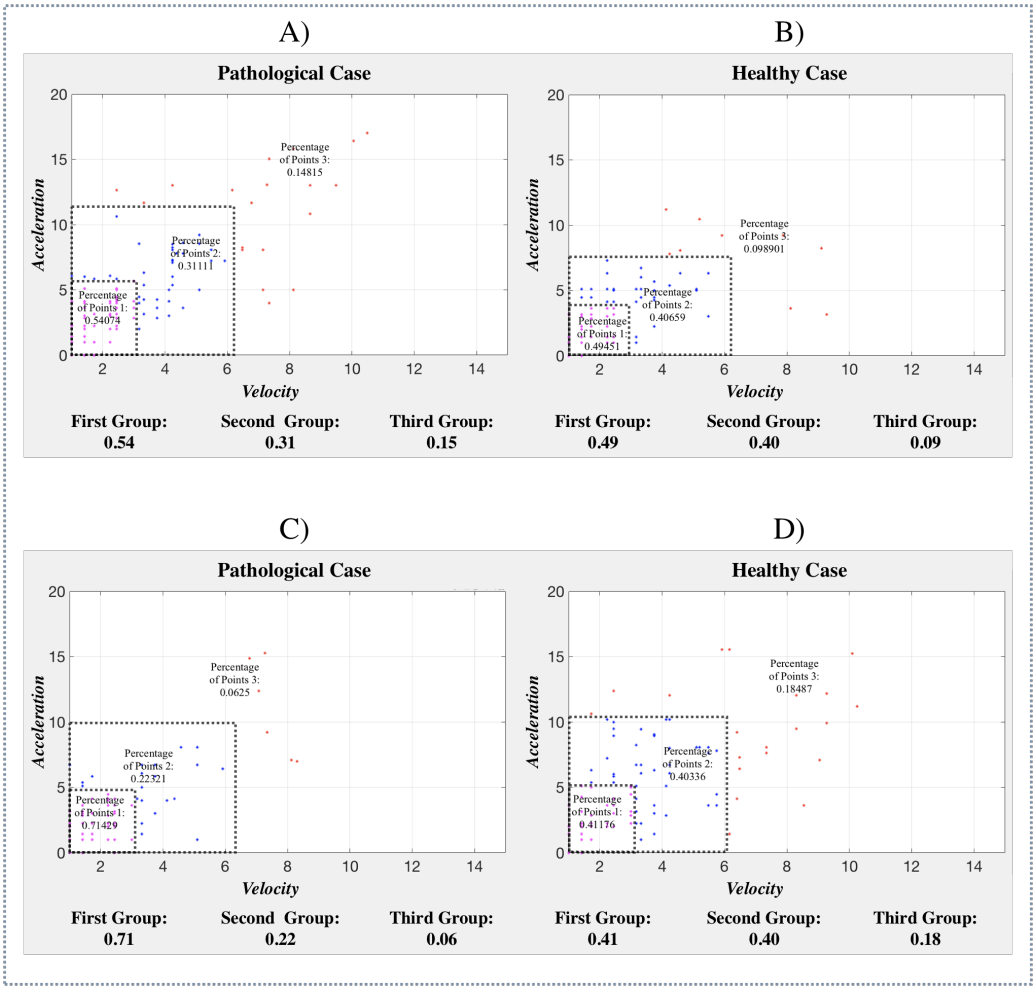

Figure 3-11: Comparing results: cases A) and C) corresponding to pathological ones, B) and D) corresponding to control cases.

	Healthy Case 2	Healthy Case 1	Mean	Pathological Case 1	Pathological Case 2	Mean
Low Motion Region	0.41	0.49	0.45 (0.6)	0.54	0.72	0.63 (0.13)
Mid Motion Region	0.40	0.41	0.40 (0.01)	0.31	0.22	0.26 (0.06)
High Motion Region	0.19	0.10	0.15 (0.06)	0.15	0.06	0.11(0.06)

Table 3-1: Density of points per subject and density means for healthy and unhealthy cases.

3.4. Conclusions

This work introduces a novel analysis of the cardiac chamber dynamics. Results effectively show motion differences in regions of low and mid velocity-acceleration. The density at regions of low velocity-acceleration in infarcted subjects is coherent with motion limitations. Of course a main limitation of this study is the number of cases, and as future work, the characterization will be tested in a larger database.

4 Conclusions and perspectives

This thesis has introduced a novel characterization of the cardiac dynamics that manages to show a recently explored relationship between the cardiac muscle and blood. The characterization is based on a regional tracking of specific areas of the Left Ventricular Chamber (LVC), that is to say the areas where the muscle and the blood are interacting, allowing to observe not just the inherent relationship between these two tissues but also to find out associations with previously described motion limitation findings for cases with ischemic diseases, produced by the lose of motion capabilities due to scar tissue formation following an infarction. The presented strategy may provide a new indicator of the cardiac function.

Additionally, at the image processing step, this work has introduced a pre-processing strategy based on oriented structuring elements. The filtering technique is based on a bank of morphological multi-scale and multi-orientation elements that is operated with an input image to produce different versions of this image in order to preserve relevant information, later the image versions are averaged in order to obtain a representative image, that is to say, an output filtered image that removes most of the speckle noise and preserves delicate cardiac structures. This method is partially implemented across the thesis in order to highlight relevant motion information inside the LVC, permitting to implement the previously described regional tracking.

Overall, this work has contributed in the characterization and exploration of cardiac dynamics as a tool to assess the cardiac function. Some first results comparing the behaviour of infarcted and non-infarcted cases are shown, proving that further exploratory studies may be conducted in order to improve the assessment of CVDs and to deepen in the understanding of the heart function. The presented results show that a new indicator of the cardiac function based on the changes of velocity and acceleration is feasible, this may be a valuable tool in clinical environments given the fact that the presented strategy is easily implementable, for this case in a common use computer, namely, a MacBook Pro 13-inch (2011) with 8GB of RAM and a Intel Core i5 (2,4GHz) 3rd generation processor. This document also features a pre-processing strategy that improves the segmentation of certain cardiac structures by reducing speckle noise that hinders the capabilities of segmentation algorithms and clinicians to identify relevant structural information.

Finally, it is worth to mention that the evaluation of the presented work has been performed with publicly available data, in this case from the 2014 MICCAI Challenge on Endocardial Three-Dimensional Ultrasound Segmentation (CETUS). Initially, this database was constructed in order to compare several left ventricle segmentation methods, but thanks to it, it was possible to test the presented strategies. From the previously stated, the need of further work in order to validate both strategies with more diverse data from different ultrasound machines with different capture conditions as well as different pathological conditions, is exposed.

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