

CHAPTER 4

RESULTS AND DISCUSSION

The integration of Computed Tomography (CT), Magnetic Resonance Imaging (MRI), and Ultrasound (US) has the potential to offer complementary information, enhancing the evaluation and display of comprehensive structural details. Consequently, valuable insights are derived from all three modalities. This integration addresses the challenges of synchronizing the temporal aspects and spatial orientation of moving heart images. Subsequently, this chapter presents a collection of outcomes obtained using the recommended automatic registration technique. The registration functionality of this technique has been validated in a study involving twenty recruited patients. Section 4.1 presents the results of the temporal registration of US images and the most reliable matching of CT and MRI planes. These results specifically include the identification of the “Mercedes Benz” indication observed in the images of the aortic valve.

In Section 4.2, a comparison is made between the best matching plane obtained through the suggested method and the outcomes of manual gold registration. The manual segmentation of CT and MRI aortas is presented in Section 4.3. This process involves delineating the contours of the aortas manually. Section 4.4 provides the results of computations for metrics such as the Dice Similarity Coefficient (DSC) and Hausdorff Distance (HD). Note that these quantitative measures are calculated explicitly for the contoured region of the acquired aortic valve view. Section 4.5 reports the measurements of the diameter of the aortic valve, along with an analysis of Bland-Altman plots. Section 4.6 presents each transformation parameter's Root Mean Square

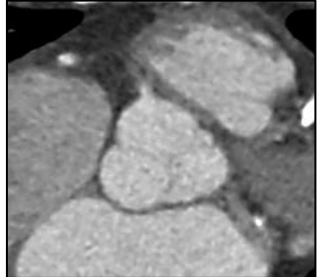
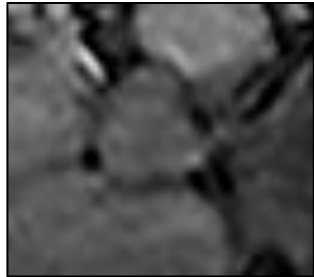

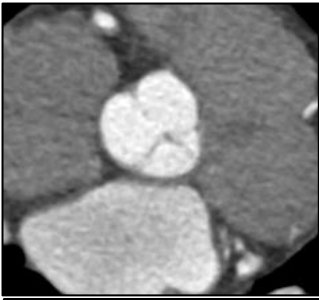
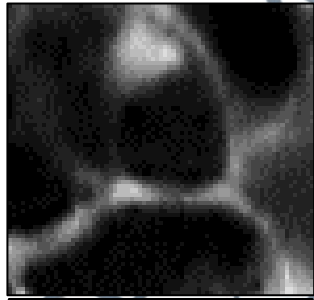
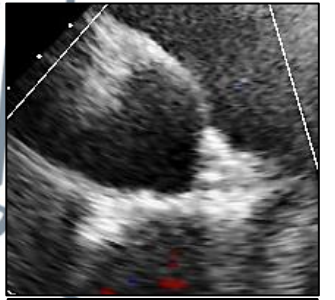

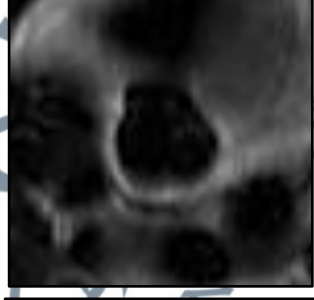


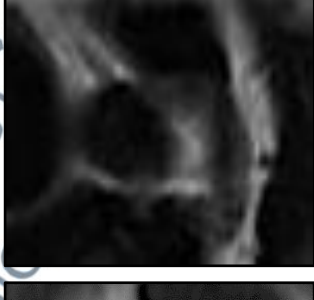


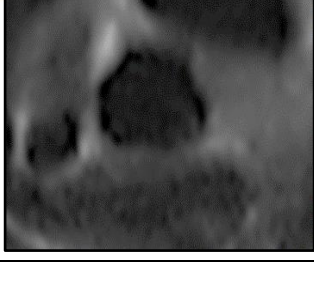
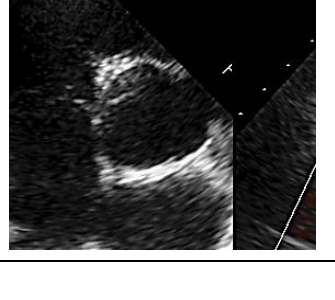
Error (RMSE) and other quantitative error analyses. Lastly, Section 4.7 shows registered images of the US with cardiac CT and MRI from two separate patients. These images demonstrate the successful registration of different modalities, highlighting the potential of the suggested method for integrating multiple imaging techniques.

4.1 Trimodality Automatic Image Registration Results

The integration of US, CT, and MRI in cardiovascular imaging offers valuable baseline data that can aid in decision-making processes and provide a comprehensive assessment of disease spread and characteristics. Using a proposed intensity-based registration algorithm, this research applied a rigid geometrical transformation to the two-dimensional (2D) planar US images. This transformation allowed the US images to be aligned with the surrounding area of the cardiac CT and MRI volumes, enabling the identification of the most suitable matching cardiac CT and MRI planes.

Table 4.1 presents five examples of automatic image registration using the trimodality approach. The CT and MRI images displayed in the table were generated using the suggested automated registration technique, while the US images were obtained through temporal synchronization. The fusion of US, CT, and MRI images becomes possible using the proposed registration algorithm, providing a comprehensive visualization of the cardiovascular structures. This integration enables clinicians and researchers to analyze and interpret the data more effectively, aiding in understanding diseases and facilitating more informed decision-making processes. The examples in Table 4.1 illustrate these different imaging modalities' successful alignment and merging, highlighting the potential benefits of trimodality image registration in cardiovascular imaging.

Table 4.1: CT-MRI-US Automatic Registration Results of The Aortic Valve Sign “Mercedes Benz” on Five Patients

Patient	Computed Tomography (CT)	Magnetic Resonance Imaging (MRI)	Ultrasound (US)
1			
2			
3			
4			
5			

4.2 Manual Registration Results

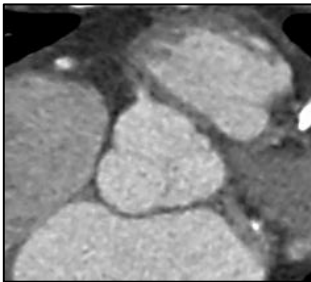
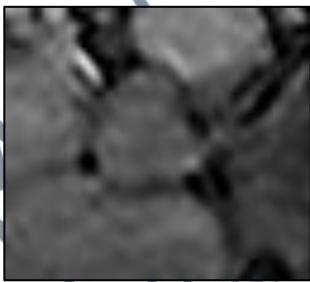
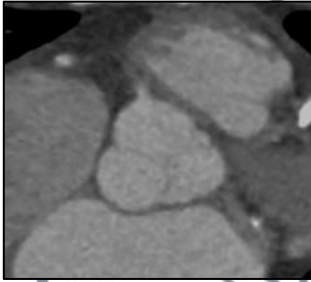
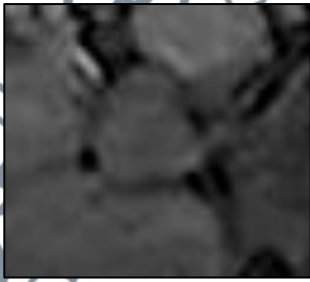
To validate the accuracy of the automatic registration algorithm, experts from the Radiology Department at Hospital Serdang, Selangor, Malaysia, conducted a manual registration process. These experts possessed extensive anatomical knowledge and were well-versed in the field.

During the manual registration, the experts discovered that manually manipulating the transformation parameters could achieve high similarity between the interpolated CT and MRI images and the 2D US image. The results of this manual registration process are presented in Table 4.2, with the first row indicating the automatically registered CT and MRI images and the second row displaying the CT and MRI images that an expert manually registered.

The comparison between the manually registered CT and MRI images and the automatically registered ones revealed that both sets exhibited similar features when visualizing aortic structures. In other words, the aortic structures in the automatically registered CT and MRI images closely resembled those in the manually registered images, as observed by the expert.

In conclusion, the manual registration process served as a benchmark to evaluate the accuracy of the automatic registration algorithm. The experts achieved comparable results through manual manipulation of transformation parameters, and the automatic registration algorithm demonstrated a similar level of accuracy in reproducing the aortic structures observed in the manual registration process.

Table 4.2: An Observation of The Difference in “Mercedes Benz” View CT and MRI Scans Registered Automatically and Manually

Types of registration	Types of imaging	Computed Tomography (CT)	Magnetic Resonance Imaging (MRI)
Automatic			
			

The image quality of the interpolated CT and MRI images was assessed for both automatic and manual registration using Cohen κ statistics. Out of the total number of images evaluated, 100, there were observed agreements in 93% of the cases. Among these agreements, 54 images (54%) were rated as grade 1, indicating outstanding image quality, while 46 images (46%) were rated as grade 2, indicating good image quality. None of the readers assessed the image quality as grade 3 (poor but still diagnostic image quality) or grade 4 (bad image quality). Note that significantly high agreement with a κ value of 0.858 was observed in the overall image quality assessment across all 20 patients. It indicates a strong level of agreement between the automatic and manual registration methods in terms of image quality.

4.3 Manual Aortic Segmentation

Figures 4.1 and 4.2 illustrates the outcomes of a manual segmentation technique employed in image registration. This method was used to segment the aortic valve on CT and MRI images. The segmentation results were obtained through two approaches: manual and automatic registration. In the images, the segmented contours of the aortic valve cross section are highlighted in green and can be observed within the views resembling the shape of a “Mercedes Benz” sign.

Registered Manual CT (left image) and MRI (right image)

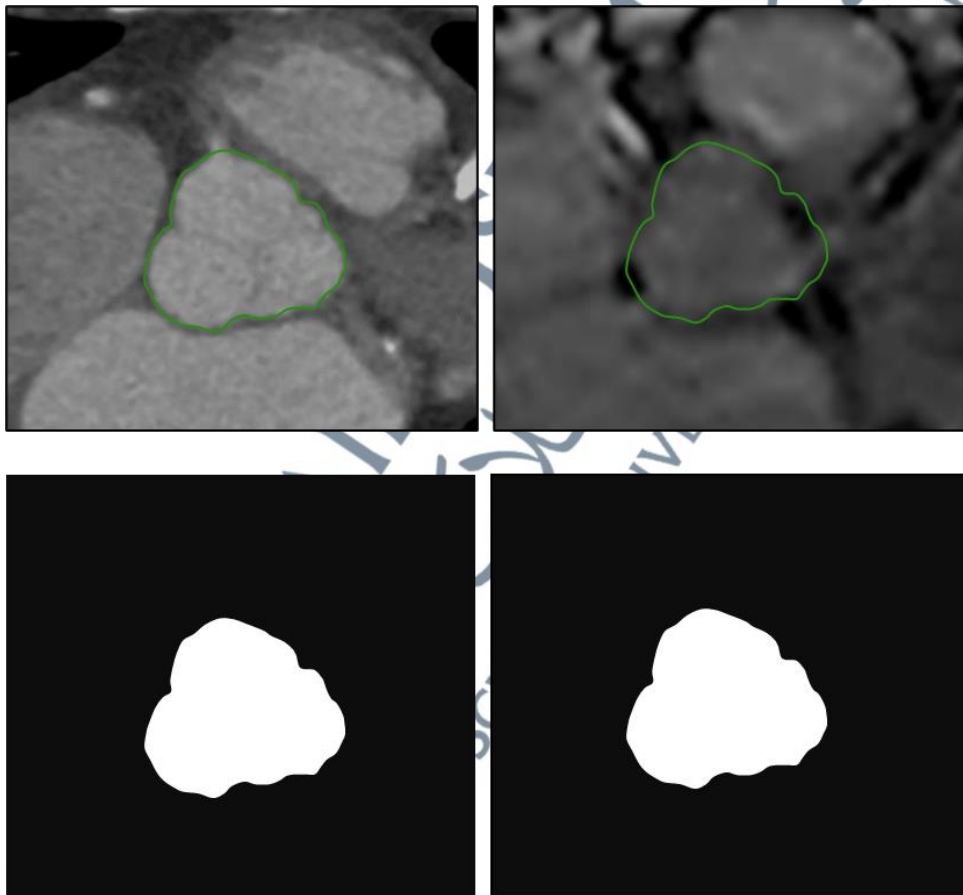


Figure 4.1: Manual Segmentation of The Aortic CT and MRI Images from Manual Registration

Registered Automatic CT (left image) and MRI (right image)

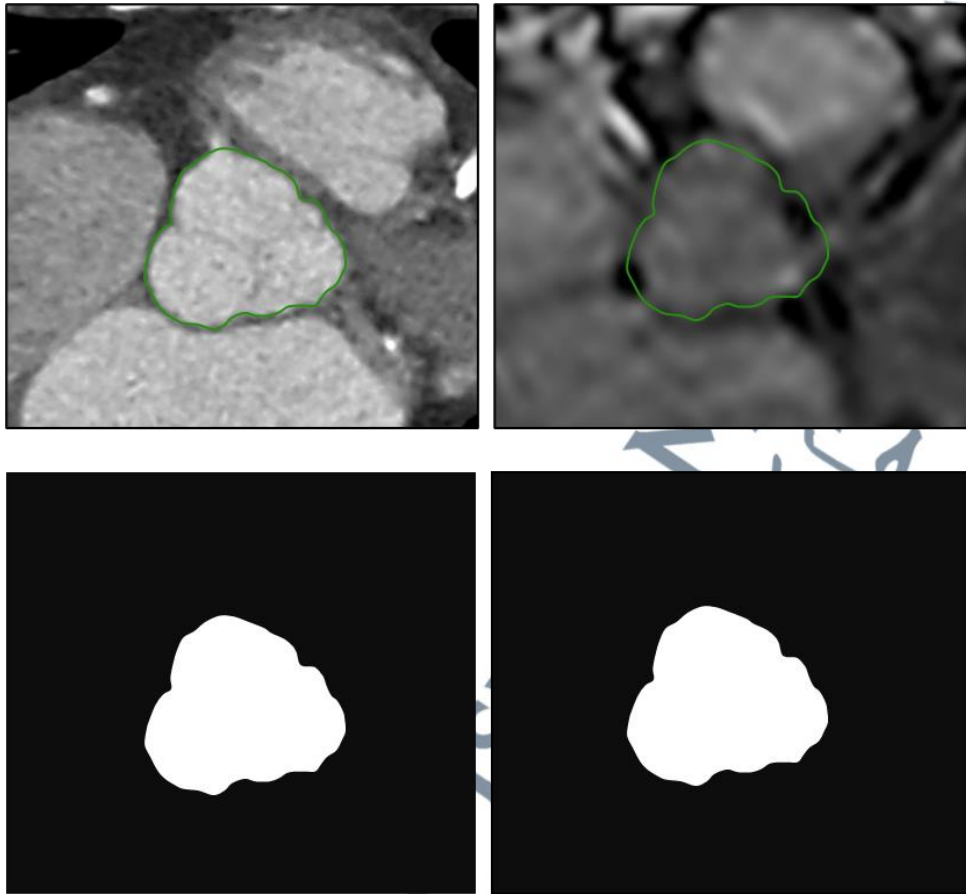


Figure 4.2: Manual Segmentation of The Aortic CT and MRI Images from Automatic Registration

4.4 Results from The Computation of DSC and HD

In order to determine registration precision quantitatively, DSC and HD metrics were calculated. Table 4.3 summarizes the DSC and HD values of the shared characteristics identified in the US with CT and MRI planes. In short axis “Mercedes Benz” sign views, DSC values were similar between US-CT and US-MRI, at $0.92 (\pm 0.05)$ and $0.92 (\pm 0.04)$, respectively. If the DSC value is greater than 0.7, the contoured ROI in the images shares a significant overlap in area size and location. A higher DSC value indicates a better agreement in terms of size and placement between the two compared contours, leading to more precise segmentation outcomes.

HD was similarly calculated between the two pairs of registration, with the first pair having a value of 1.49 (± 0.20) mm and the second pair having a value of 1.49 (± 0.19) mm. Given the substantially larger field of view generated by both imaging modalities, for example, 0.7 x 0.7 x 0.7 mm for CT and MRI volume and 0.6 x 0.6 mm for a US plane, this registration error of roughly 6 to 7 pixels is acceptable. Other than that, all patient data sets were satisfactorily segmented, and US-CT and US-MRI present good similarity and minimally dissimilar contour shapes.

Table 4.3: Calculation of DSC and HD Values Between US-CT and US-MRI

Patient	DSC		HD	
	US-CT (Mean \pm Std)	US-MRI (Mean \pm Std)	US-CT (Mean \pm Std)	US-MRI (Mean \pm Std)
1	0.76 \pm 0.03	0.78 \pm 0.05	1.31 \pm 0.11	1.33 \pm 0.14
2	0.85 \pm 0.03	0.83 \pm 0.06	1.35 \pm 0.26	1.38 \pm 0.21
3	0.89 \pm 0.04	0.88 \pm 0.04	1.34 \pm 0.02	1.33 \pm 0.07
4	0.90 \pm 0.02	0.91 \pm 0.02	1.36 \pm 0.30	1.36 \pm 0.32
5	0.91 \pm 0.05	0.92 \pm 0.02	1.36 \pm 0.43	1.39 \pm 0.42
6	0.91 \pm 0.04	0.90 \pm 0.03	1.37 \pm 0.12	1.35 \pm 0.12
7	0.92 \pm 0.06	0.92 \pm 0.03	1.39 \pm 0.07	1.40 \pm 0.01
8	0.92 \pm 0.04	0.92 \pm 0.04	1.40 \pm 0.15	1.38 \pm 0.05
9	0.93 \pm 0.03	0.91 \pm 0.03	1.41 \pm 0.04	1.43 \pm 0.18
10	0.93 \pm 0.06	0.91 \pm 0.02	1.41 \pm 0.20	1.45 \pm 0.22
11	0.93 \pm 0.03	0.95 \pm 0.05	1.42 \pm 0.16	1.36 \pm 0.10
12	0.93 \pm 0.04	0.94 \pm 0.03	1.44 \pm 0.11	1.49 \pm 0.16
13	0.94 \pm 0.02	0.94 \pm 0.04	1.47 \pm 0.25	1.50 \pm 0.21
14	0.94 \pm 0.01	0.95 \pm 0.04	1.50 \pm 0.09	1.48 \pm 0.04
15	0.94 \pm 0.02	0.95 \pm 0.03	1.53 \pm 0.02	1.50 \pm 0.04
16	0.95 \pm 0.03	0.94 \pm 0.05	1.54 \pm 0.12	1.55 \pm 0.12
17	0.95 \pm 0.05	0.93 \pm 0.02	1.57 \pm 0.14	1.55 \pm 0.10
18	0.95 \pm 0.03	0.96 \pm 0.01	1.58 \pm 0.21	1.57 \pm 0.18
19	0.95 \pm 0.02	0.93 \pm 0.05	1.96 \pm 0.32	1.90 \pm 0.29
20	0.96 \pm 0.02	0.95 \pm 0.03	2.08 \pm 0.25	2.10 \pm 0.30
Mean \pm Std	0.92 \pm 0.05	0.92 \pm 0.04	1.49 \pm 0.20	1.49 \pm 0.19

The registration was performed independently between the US-CT and US-MRI for each patient. To expand our research into trimodality approaches, we used both US-

CT and US-MRI to compute DSC and HD graph values. This allowed us to discover whether the accuracy of US-CT and US-MRI is consistent between the two pairs. Figures 4.3 and 4.4 illustrate two different graphs of DSC and HD, respectively.

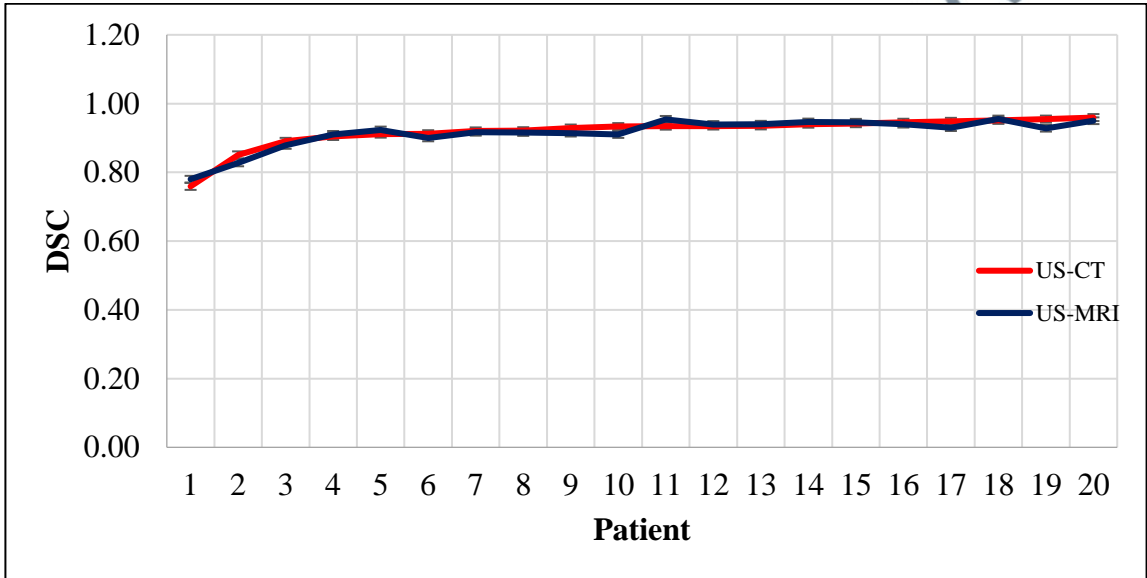


Figure 4.3: DSC Between US-CT and US-MRI

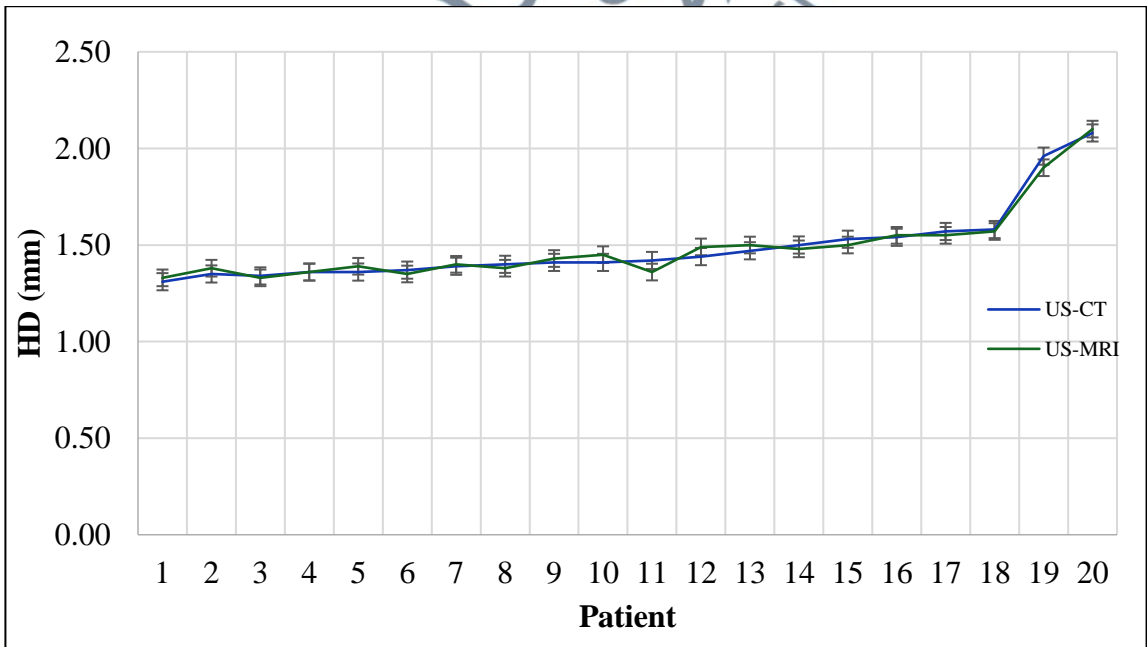


Figure 4.4: HD Between US-CT and US-MRI

4.5 Bland-Altman Analysis

Both automatic and manual registration of CT and MRI images were used to measure aortic diameters. The Bland-Altman analysis assessed the degree of agreement between the automatic registration method and the gold standard manual registration. This graphical method allowed for visualizing the difference between the two measurements relative to the mean of the identical measurements, highlighting their disparity.

Figure 4.5 displays a Bland-Altman plot illustrating a favorable agreement in the aortic valve annulus diameter measurements obtained from both automatically and manually registered CT images. The range of variation in the measurement of the aortic valve diameter was approximately -0.31 ± 1.38 mm, indicating an agreement within a range of approximately -2.39 to 3.01 mm.

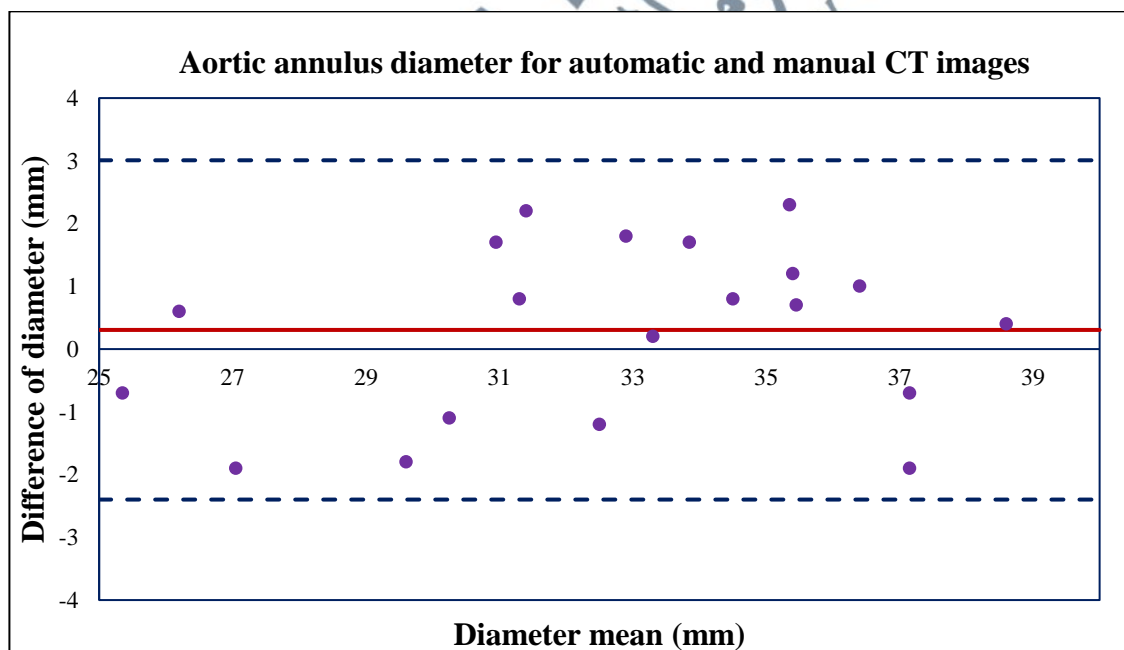


Figure 4.5: Diameter of The Aortic Valve as Measured by CT scans, With 95% Limits of Agreement (Blue Dotted Line) And Bias (Red Line) For Both the Automatic and Manual Registration Methods

In contrast, as portrayed in Figure 4.6 below, the mean difference for aortic valve diameter measurements was determined to be -0.10 1.50 mm, with a limit of agreement of around -2.85 to 3.05 mm. The CT and MRI scans displayed no substantial bias in the Bland-Altman plots, indicating that the registration procedures were accurate.

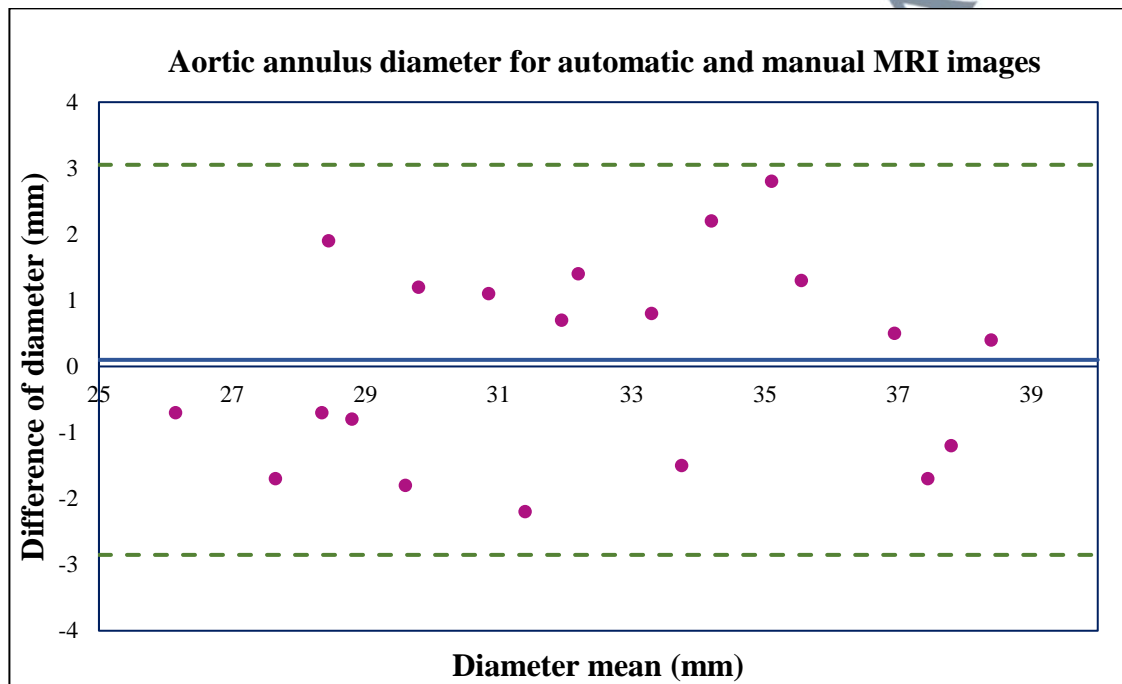


Figure 4.6: Diameter of The Aortic Valve as Measured by MRI Scans, With 95% Limits of Agreement (Green Dotted Line) And Bias (Blue Line) For Both the Automatic and Manual Registration Methods

4.6 Root Mean Square Error

The RMSE was calculated for each transformation parameter for quantitative analysis. Tables 4.4 and 4.5 summarizes the statistical deviation from the ideal values of the transformation parameters between automatic and manual registration of CT and MRI in the US. The RMSE for translation of US-CT and US-MRI is between 0 and 2.10 mm and between 0 and 2.13 mm, respectively. It is almost equivalent in magnitude to the resolution of cardiac CT and MRI using the US, which is between 0 and 5 pixels. Note that the angle difference between the two is less than 3, and the least scaling difference was recorded.

Table 4.4: Difference in RMSE Between US-CT Automatic and Manual Registration for 20 Patients

Patient #	Translation (mm)			Rotation (°)			Scaling	
	Δtx	Δty	Δtz	Δa	$\Delta \beta$	$\Delta \gamma$	Δsx	Δsy
1	0.07	0.14	0.02	0.03	0	0.16	0	0
2	0	0.06	0.42	0.11	0	0.22	0	0
3	1.58	0.04	0.03	0.24	0	0.49	0	0
4	0.23	0.05	1.70	1.79	0	0	0	0
5	0.17	0.23	0.01	0.03	0	0.17	0	0
6	0.42	1.13	0	0.45	0	0.20	0	0
7	1.7	0.07	0.06	0	0	0	0	0
8	0.22	2.10	0.78	0	2.10	2.35	0	0
9	0	1.13	0.01	0.43	0	0	0	0
10	0.03	0.27	0.06	0.03	0	0.16	0	0
11	1.7	0.04	0	0.24	0	0.47	0	0
12	0.02	0.01	0.22	1.88	0	0	0	0
13	1.91	0.13	0	0.03	0	0.16	0	0
14	0	0.02	0.07	0.47	0	0	0	0
15	0	0.28	0.01	0	0	0	0	0
16	0.42	1.13	1.70	0.03	0	0.18	0.01	0
17	0.14	2.09	0	0	2.59	2.44	0	0
18	0.03	0.07	0.42	0.02	0	0	0	0
19	0.22	2.05	0.06	1.10	0	0.22	0	0
20	0	0.04	0.01	0.21	0	0.55	0	0

Table 4.5: Difference in RMSE Between US-MRI Automatic and Manual Registration for 20 patients

Patient #	Translation (mm)			Rotation (°)			Scaling	
	Δtx	Δty	Δtz	Δa	$\Delta \beta$	$\Delta \gamma$	Δsx	Δsy
1	0.08	0.24	0.02	0.10	0	0.16	0.01	0
2	0	0.08	0.30	0.02	0	0.14	0	0
3	1.58	0.05	0.04	1.14	0	0.07	0	0
4	0.13	0.02	0.95	0.39	0	0.02	0	0
5	0.17	0.19	0.03	0.03	0	0.17	0	0
6	0.40	1.13	0	0.45	0	0.20	0	0
7	1.65	0.05	0.02	0	0	0	0	0
8	0.22	2.13	0.78	0	2.10	2.35	0	0
9	0	1.13	0.01	0.43	0	0	0	0
10	0.03	0.27	0.06	0.03	0	0.16	0	0
11	0.7	1.04	0	0.24	0	0.47	0	0
12	0.02	0.01	0.07	1.78	0	0	0	0
13	1.80	0.20	0	0.02	0	0.16	0	0
14	0.01	0.12	0.02	0.47	0	0	0	0
15	0	0.28	0.01	0	0	0	0	0
16	0.42	1.04	1.60	0.03	0	0.18	0.01	0
17	0.14	2.10	0.2	0	2.59	2.44	0	0
18	0.02	0.09	0.42	0.02	0	0	0	0
19	0.21	2.05	0.06	1.10	0	0.22	0	0
20	0	0.08	0.01	0.21	0	0.55	0	0

4.7 Trimodality US-CT-MRI Fusion Image

The US and the interpolated best-matching plane of CT and MRI were combined to guide surgeries. Three sets of registered images from different patients are demonstrated in Figures 4.7, 4.8 and 4.9. All the examples present a composite view of US, CT, and MRI images from a short axis “Mercedes Benz” sign perspective. The US image serves as the “reference” or “fixed” image, while the CT and MRI images are considered the “target” or “moving” images. The green and red images, derived from CT and MRI, respectively, represent the moving images. Meanwhile, the blue image from the US serves as a reference for the other two. Each figure precisely shows aligned aortic valves. The proposed registration approach accurately aligns the images required

for clinical applications, as confirmed by an expert's visual evaluation of overlapping cardiac structures.

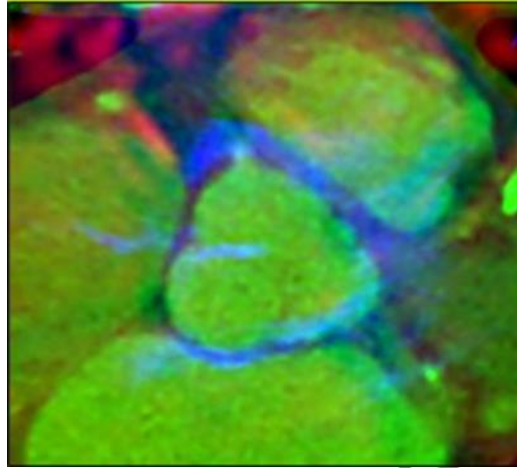


Figure 4.7: Registration Result of US, CT, and MRI on Patient 1 at “Mercedes Benz” Sign View

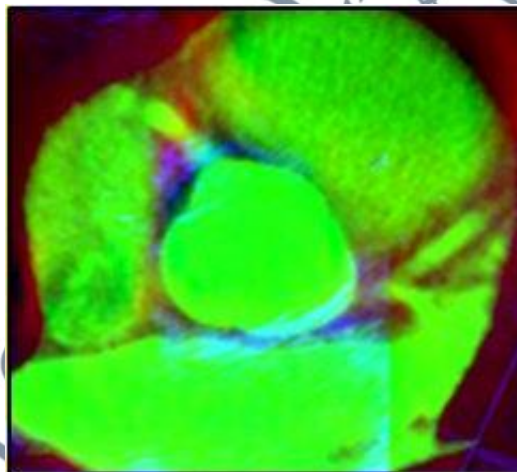


Figure 4.8: Registration Result of US, CT, and MRI on Patient 2 at “Mercedes Benz” Sign View

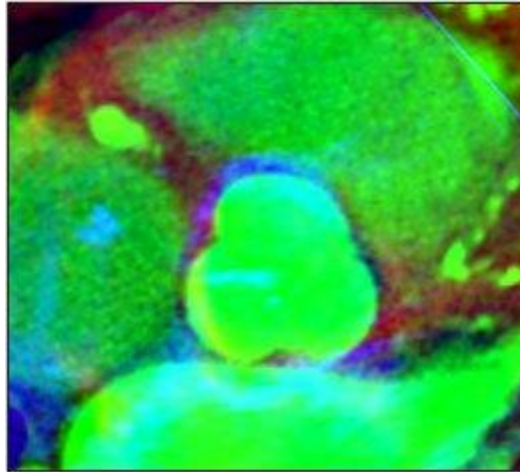


Figure 4.9: Registration Result of US, CT, and MRI on Patient 3 at “Mercedes Benz” Sign View

4.8 Major Findings of The Study

Fusion imaging is increasingly used to guide interventional operations. Strategies generally focus on combining US imaging with additional modalities, such as cardiac CT and MRI. A trimodality imaging system can display all the images in real-time (Liang et al., 2014). Hence, CT scans and MRI procedures are essential in diagnosing cardiovascular-related diseases. Cross-sectional heart images benefit the physician because they provide complete anatomical information. However, real-time imaging is impossible due to the high radiation in CT (Prat-Gonzalez et al., 2008; Sun, 2013), and MRI requires an extended period for image acquisition. Meanwhile, US imaging provides real-time imaging of the heart structure, allowing the physician to assess the anatomical, functional, and hemodynamic changes. Nevertheless, the constraint of the US is due to the limited Field of View (FOV) and low-quality details in the images (Ewertzen et al., 2013; Otto, 2007).

A fusion of the three modalities compensates for CT, MRI, and US limitations and will help the physician obtain complete information. This fusion can be used as a guided image intervention during heart treatment. US-CT-MRI merging for

cardiovascular application could provide additional baseline data that could aid in decision-making to evaluate the spread of the diseases. To aid in the treatment of Cardiovascular Diseases (CVD), especially aortic valve dysfunction, a registration framework has been presented in this study. This framework fuses three-dimensional (3D) cardiac CT and MRI images with 2D US frames. In addition, they can be utilized as a tool for intraprocedural navigation in treating CVD.

Since all imaging modalities provide images with varying sampling latencies and temporal resolution, this study conducted temporal registration to synchronize US with cardiac CT and MRI images in time. Preprocessing was performed on the US image frames interpolated from the time series echocardiogram recording to lessen the amount of speckle noise in the final product. Consequently, the expert visual evaluation confirms that the suggested temporal registration methods can successfully synchronize the temporal sequence of US images.

The proposed method is utilized for the data that was previously collected at the moment. In the temporal registration process, it was discovered that the automatically registered CT and MRI images matched their respective US views, which were taken from a time series data set. It was done to complete the automatic registration process. Furthermore, the proposed spatial registration approach was assessed by contrasting it with the gold standard registration method, manual registration. Automatically registered CT and MRI planes were considered by the expert to be visually consistent with manually collocated CT and MRI planes with regard to the appearance of cardiac structures. Visually and quantitatively assessing the aortic diameter between the respective interpolated planes, the automatically registered CT and MRI images have demonstrated good agreement with the CT and MRI images manually selected by an expert.

The proposed approach is currently being applied to retrospective data. Validation results suggest that the proposed technique has a high level of accuracy for identifying CVDs, particularly those affecting the aortic valve. According to Cohen's data, observers strongly agree regarding the overall image quality for all twenty patients. Besides, the DSC values that were recorded were higher than 0.7. It indicates that there is a significant resemblance in terms of size between the contoured ROI in US-CT and US-MRI images. A high value for the DSC measure indicates that the segmentation findings are accurate if the two contours being compared are aligned in size and position. In contrast, the distance inaccuracy indicated by the reported HD is almost the same as the resolution of CT and MRI in the US or about six to seven pixels. It is tolerable because both imaging methods provide a significantly larger FOV than the 2D US; for example, 0.7 mm x 0.7 mm x 0.7 mm for a CT or MRI volume, and a 2D US plane is 0.6 mm x 0.6 mm.

The Bland-Altman plots present that the diameter measurement of the valve's annulus, derived from automatically and manually registered CT and MRI planes, has a reasonable agreement between the two data sets. In addition, the RMSE of the translation, rotation, and scaling parameters of US-CT and US-MRI was small. Furthermore, the information the registered trimodality US-CT-MRI images provides is vastly more complimentary than any modality working alone. These validation outcomes demonstrate a promising accuracy of the suggested technique for navigation throughout the treatment procedure and enhance image-guided systems for CVD, particularly in Transcatheter Aortic Valve Implantation (TAVI) and Transcatheter Aortic Valve Replacement (TAVR) operations. They rely heavily on a clear picture of the heart's anatomy, and the proposed approach has proven successful.

In order to facilitate the guidance of TAVI and TAVR procedures, a novel image registration framework for information fusion between 2D US, 3D cardiac CT, and MRI was introduced in this study. For a quick and precise evaluation of the aortic valve structures in the “Mercedes Benz” perspective, the suggested registration system aims to create a spatial relationship between the anatomical and functional data found in different types of imaging. Note that these details are essential for preoperative planning and may help lower the risk and morbidity of the therapy intervention. The interpretability of intraoperative 2D US images has been discovered to enhance significantly inside the high-quality dynamic 3D anatomical context offered by CT and MRI imaging.

4.9 Comparison with Comparable Studies from The Past

The study examined the accuracy of a registration method that compares US images with CT and MRI images. The reported distance error, specifically in terms of HD measurement, was between 1.49 ± 0.20 mm and 1.49 ± 0.19 mm, as presented in Table 4.3. It means that the registration method had an average error of approximately 1.49 mm, with a slight variation.

The observed error can be attributed to various factors. One factor is the spatial registration errors when aligning US images with CT and MRI planes. These errors can arise due to differences in the positioning and orientation of the imaging devices. Another factor is the physical variations of the same structure imaged by US, CT, and MRI. Since each imaging modality captures images using different principles and techniques, there may be inherent differences in the appearance of structures. Lastly, the manual delineation of cardiac structures for comparison can introduce variability,

as different individuals may have slightly different interpretations and techniques for delineation.

It is important to note that no similar study with comparable results was established in the existing literature up until June 2023. Therefore, the reported error values in this study cannot be directly compared to those from other studies. However, the study did include a discussion and presentation of a comparison of registration accuracy based on distance error with some related works on cardiac registration, as presented in Table 4.6. It provides a point of reference for understanding the performance of the registration method with other approaches discussed in the literature.

In their study, Huang et al. (2009) reported a Target Registration Error (TRE) of 1.7 ± 0.4 mm when registering 2D US images to cardiac CT using a phantom. Additionally, Lang et al. (2011) developed a registration framework to align US with CT scans, which yielded a TRE of 1.5 ± 0.45 mm specifically for the aortic root. On the other hand, Khalil et al. (2017b) proposed registration frameworks for US to CT and reported a TRE of 1.32 ± 0.04 mm specifically for the aortic valve. Note that these studies employed optical tracking systems in their registration frameworks, except for Khalil et al. (2017b). Despite the absence of an optical tracker for the registration process, the proposed registration method in this research demonstrated a lower TRE than what has been reported in previous studies in the literature. Table 4.6 summarizes the relevant studies, highlighting their respective Regions of Interest (ROI) and the reported differences in distance error compared to the current study conducted using US and CT. According to the information provided in Table 4.6, it is evident that the proposed approach exhibits a slightly different and reduced distance error in comparison to the findings of other studies.

Table 4.6: Differences in Distance Errors Among The Studies Conducted Using US and CT

Type of study	Research studies	Region of interest	Distance error (mm)
Previous	(Huang et al., 2009)	Phantom	1.7 ± 0.4
	(Lang et al., 2011)	Aortic root	1.5 ± 0.45
	(Khalil et al., 2017b)	Aortic valve	1.32 ± 0.04
Current		Aortic valve	1.49 ± 0.20

Meanwhile, there is no any comparative study in the literature that specifically investigated the fusion of the US with MRI to evaluate the aortic valve. Nonetheless, the study did discuss and present a comparison of registration accuracy based on distance error, drawing from other research on cardiac registration that employed US and MRI. One such study by Huang et al. (2005) proposed a method for registering US and MRI images of a beating heart. This technique holds promise for enhancing the ease and precision of diagnosing cardiac diseases, as well as facilitating surgical planning and guidance. The study reported an average distance error of 0.86 ± 0.40 mm. Although this result is smaller than the values observed in the current study, both results remain reasonable outcome. Table 4.7 provides an overview of the related studies, the region of interest (ROI), and the reported distance error, allowing for a comparison with the present study that employed US and MRI.

Table 4.7: Differences in Distance Errors Among The Studies Conducted Using US and MRI

Type of study	Research studies	Region of interest	Distance error (mm)
Previous	(Huang et al., 2005)	Beating Heart	0.86 ± 0.40
Current		Aortic valve	1.49 ± 0.19

4.10 Clinical Significance of The Research

Cardiovascular imaging plays a crucial role in diagnosing and planning cardiac surgeries. However, integrating data from different imaging modalities, such as CT,

MRI, and US, is essential for accurate diagnosis and effective preoperative planning. Image registration, specifically the trimodality registration of CT, MRI, and US images, holds significant clinical significance in CVD.

Modern imaging technologies like CT and MRI provide high-quality images for assessing cardiac structure and function. However, there are limitations in terms of real-time capabilities and cost. These technologies are not always readily available and require specialized facilities. On the other hand, the US is a portable and affordable imaging modality that enables real-time imaging. However, the presence of speckle noise in US images makes interpretation challenging.

Combining preoperative cardiac CT and MRI images with high contrast and detailed information with intraoperative 2D US images makes diagnosing much easier. The trimodality approach of US-CT-MRI can be highly effective in cardiovascular treatment, particularly in guidance for TAVI and TAVR. It overcomes the limitations associated with using a single imaging modality.

The most common and minimally invasive therapeutic modalities recommended for patients with aortic valve disorders include 2D US, cardiac CT, and MRI. By leveraging the advantages of each modality and combining them through image registration, physicians can improve the accuracy of diagnosis and enhance preoperative planning for cardiovascular interventions. Other than that, trimodality image registration holds promise for improving patient outcomes in treating CVD.

4.11 Limitation of The Research and Suggestion for Improvement

Several limitations were identified in the research and are outlined in the subsequent subsections. Additionally, suggestions for enhancing these existing limitations are also presented.

4.11.1 The Heart as A Solid Structure

It is widely believed that the heart remains rigid and undergoes periodic motions throughout the imaging process. Hence, the current techniques employ a rigid spatial transformation in the registration process. This approach is commonly utilized in clinical practice and is deemed acceptable for achieving accurate diagnoses. However, it should be noted that while this assumption holds in certain surgical scenarios, the heart is, in fact, a nonrigid and dynamic structure (McLeish et al., 2002). During the pumping cycle, the heart naturally undergoes deformation. Besides, factors like respiration, pressure from probes, and surgical instruments on the skin can further contribute to heart deformation. These factors challenge the accuracy of real-time image registration during imaging.

Despite relying on a rigid spatial transformation, the proposed registration method has shown promising accuracy in validation results, making it a suitable approach for guiding surgical procedures. To address the issue of heart deformation, it is suggested that the registration technique be enhanced by incorporating nonrigid registration methods. However, it is important to consider that such an improvement may introduce additional complexity to the registration process and potentially affect the registration speed.

Regarding temporal registration, a linear interpolation technique aided by the Electrocardiogram (ECG) signal was employed to synchronize US with cardiac CT or MRI. This method proved practical in cases where there were no significant variations in heart rate during the imaging sessions. However, in scenarios where substantial changes in heart rate occur between cardiac procedures, it may be necessary to employ a nonlinear temporal scaling of the ECG to achieve accurate synchronization.

4.11.2 Seed Placement

The proposed method depends on having prior information on the approximate position and orientation of the 2D US image concerning the patient's body's 3D axes. The clinician typically estimates this information during treatment planning before the surgical procedure. If the physician inaccurately positions the initial plane (seed), it could compromise the accuracy of the final CT and MRI planes derived through the optimization process. Moreover, the expertise of medical professionals influences the precision of this seed placement in understanding how US views are obtained from the patient. Consequently, specific physician training may be necessary to apply this registration technique in a clinical setting effectively.

Based on our present findings, the interpolated CT and MRI planes exhibit a low area similarity (measured by DSC) and significant differences in shape (measured by HD) compared to the US image. To achieve reliable seed placement, physicians must deeply understand how US views are acquired from the patient's body. Factors such as probe manipulation, patient positioning, and anatomical variations can affect the US image's appearance and orientation. Therefore, physicians may need specialized training and expertise to ensure accurate seed positioning during the procedure.

The success of the proposed registration technique relies on the careful coordination between the clinician's knowledge and expertise, accurate estimation of the initial US plane, and subsequent optimization steps. Considering these factors, the technique can be effectively implemented in clinical scenarios, improving accuracy and reliability in image fusion and treatment planning.

4.12 Proposed Enhancements for The Current Technique

To enhance the proposed registration techniques for US, CT, and MRI, several additional processing steps need to be implemented. For temporal registration, in cases where the heart rate remains relatively consistent, temporal synchronization between US and cardiac CT/MRI can still be achieved using linear interpolation assisted by the ECG signal. However, if there are substantial variations in heart rate between cardiac procedures, a nonlinear temporal scaling of the ECG will be necessary. Figure 4.10 illustrates the new approach incorporated into the temporal registration process to enhance the current study.

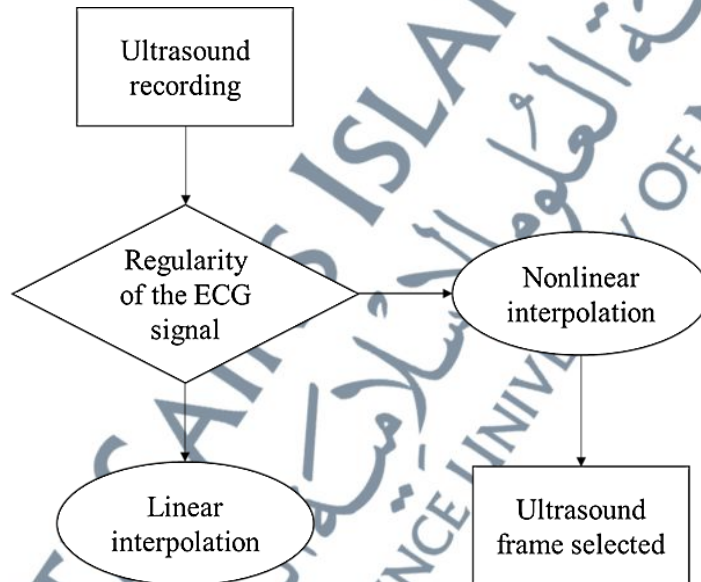


Figure 4.10: New Approach Registration Scheme Incorporated into The Temporal Registration

During the spatial registration process, which involves aligning the US frame with cardiac CT and MRI, an improved technique for real-time imaging can be achieved by utilizing a hybrid registration method. This hybrid method combines both feature-based and intensity-based schemes. By leveraging the feature-based approach, an initial estimation of the seed placement for the valve plane can be obtained, followed by fine-tuning using intensity-based registration techniques (Vos et al., 2019). This combination allows for a more accurate spatial alignment and enhances the overall effectiveness of the proposed registration technique.