Executive Summary of the Thesis

Deep-Learning-based segmentation of the aorta from dynamic 2D Magnetic Resonance Images

Laurea Magistrale in Biomedical Engineering - Ingegneria Biomedica

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Academic year: 2022-2023

1. Introduction

Non-communicable diseases (NCDs) remain the leading global cause of death, accounting for 71% of all deaths annually. A substantial portion of these deaths can be attributed to cardiovascular diseases (CVDs), which are significantly influenced by lifestyle factors, making prevention strategies essential [6].

Understanding and analyzing the dynamics of the aorta, the primary artery distributing oxygenated blood from the heart to the body, is pivotal in advancing these strategies. The aorta's unique elastic properties, which accommodate pulsatile blood flow and safeguard vital organs, deteriorate with age and disease, escalating the risk to heart health. Consequently, researching methods to accurately assess aortic health is of paramount importance [3].

To facilitate this, our project endeavors to develop an AI-based method for precisely segmenting aorta regions in dynamic MRI images, a step forward in enhancing the efficiency and accuracy of cardiovascular studies. Currently, the reliance is on phase-contrast magnetic resonance imaging techniques, which although advanced, present a range of results based on the variations in MRI systems and protocols utilized [5].

We aim to improve upon existing segmentation methods, which are often manual or semi-automated therefore time-consuming and introducing a significant degree of subjectivity and variability in results. Leveraging AI technology, we seek to automate this process, circumventing current challenges and paving the way for a deeper understanding through the analysis of larger populations, and facilitating improved clinical analysis and diagnosis.

By refining aorta segmentation techniques, the project aspires to advance current practices, enhancing the preventive strategies essential in mitigating the adverse effects of CVDs and thus, playing a pivotal role in the global health landscape. By accurately measuring and quantifying blood flow in the aorta, this project contributes to the ongoing research in cardiovascular health.

2. Materials and Methods

In this study, carried out at the Laboratoire d'Imagerie Biomédicale (LIB) in collaboration with Parisian hospitals, 2D dynamic MRI is employed to analyze the human aorta's behavior during the cardiac cycle, utilizing a dataset from 403 patients with ensured data privacy and informed consent. The DICOM standard format

is used to handle the cine MRI, velocity images, and ground truth data, aiding in thorough analysis and ensuring compatibility between various imaging devices and platforms.
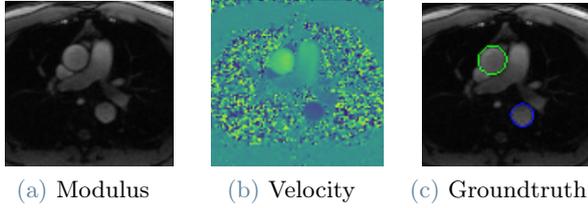

| (a) Modulus | (b) Velocity | (c) Groundtruth |

Figure 1: Images embedded in a DICOM file - Modulus, Velocity and Groundtruth on the time-resolved modulus image of a cine MRI

The UNet++ architecture, an advanced version of UNet, is utilized to enhance semantic segmentation performance. This approach integrates a nested architecture to capture multi-scale contexts more accurately, proving especially robust in handling significant variations in object sizes and shapes within the same image.
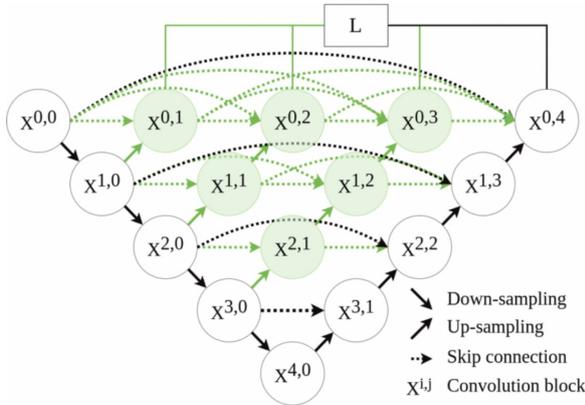

Figure 2: The backbone of the method corresponding to the UNet is represented in black and the blocks and skip connections specific to the UNet++ are represented in green, highlighting the fact that the skip-connection network is densified compared with the common UNet [7].

An initial analysis is performed using a Vanilla method based on the UNet++ architecture, with parameters meticulously chosen to manage memory overheads effectively and prevent overfitting. This method integrates batch normalization to foster speed and efficiency during the training phase, leveraging pre-trained weights from the substantial ImageNet dataset for the encoder segment of the architecture.

To narrow down the focus to the most critical sections of the cine MRI images, an ROI-centered method is developed. This approach first utilizes the Vanilla UNet model to process initial images, which guides the cropping strategy to a standard dimension of 128x128 pixels, maintaining alignment with a central midpoint established through the aggregation of initial predictions.
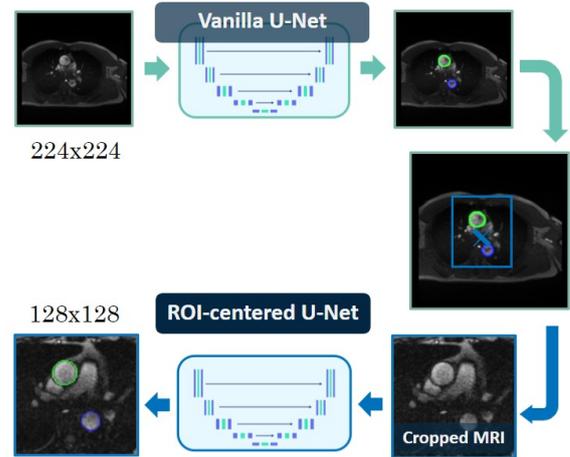

Figure 3: ROI-centered Method Schema

Further refinement leads to the creation of the AAo and DAo-centered method. This dual-focus strategy applies different cropping dimensions for the Ascending and Descending Aorta (AAo and DAo), thereby capturing each section entirely while managing computational demands efficiently. The method showcases a progression in efforts to enhance the precision and efficiency of aorta segmentation in dynamic MRI imagery.
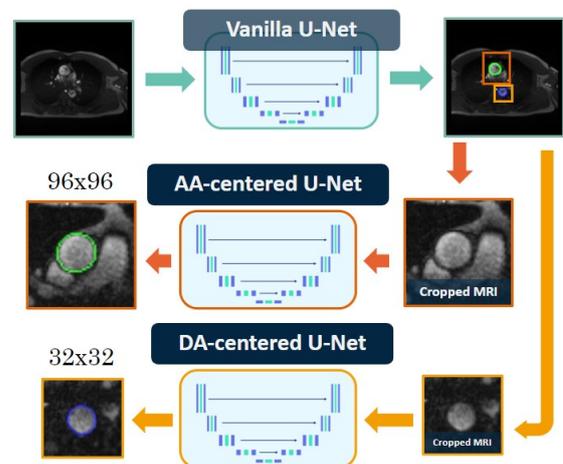

Figure 4: AAo and DAo-centered method Schema

The developed models' performance is evaluated using various metrics, each offering unique insights into their accuracy and efficiency. These include the Cross-entropy loss metric, formulated as

$$H(p, q) = -\sum p(x) \log(q(x))$$

which assesses the alignment of predicted probabilities with actual classes; the Dice coefficient, given by

$$DSC = \frac{2|A \cap B|}{|A| + |B|}$$

evaluating the overlap between predicted and ground truth segmentations; and the Hausdorff distance, defined as

$$H(A, B) = \max(h(A, B), h(B, A))$$

, which measures the largest distance from a point in one set to the closest point in the other. To quantify velocity in the ascending and descending aorta, the Mean Absolute Error (MAE)

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i|$$

and the Mean Squared Error (MSE),

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

are used, helping to highlight the average error magnitude and potential large errors, respectively. These metrics foster a deep understanding of the models' strengths and weaknesses, steering further advancements in cardiac imaging analysis.

3. Results

In our research, we compare different models to find the best one for segmenting aortas in dynamic MRI images. All the models are computationally efficient, processing a patient's cine MRI in under 2 seconds, a timeframe acceptable for our needs.

For both the ROI-centered and the AAo and DAo-centered approaches, we reintegrate the cropped regions back into the original image, ensuring a fair comparison of all three methods

Method	Dice Score	
	Ascending Aorta	Descending Aorta
Vanilla	0.972 [0.960; 0.978]	0.951 [0.937; 0.957]
ROI	0.970 [0.950; 0.973]	0.947 [0.930; 0.957]
AAo and DAo	0.976 [0.963; 0.980]	0.956 [0.946; 0.965]

Table 1: The results displayed cover the entire test set. They provide insights into the Dice score for the AAo and the DAo. Each result is formatted as Median[First Quartile; Third Quartile].

Method	Hausdorff distance	
	Ascending Aorta	Descending Aorta
Vanilla	1.10 [1.01; 1.17]	1.05 [1.01; 1.11]
ROI	1.21 [1.15; 1.33]	1.19 [1.09; 1.23]
AAo and DAo	1.10 [1.01; 1.16]	1.08 [1.04; 1.12]

Table 2: Dice Score on the whole test set applied both to the AAo and DAo, results are in the format Median[First Quartile; Third Quartile].

3.1. Results on the whole test set

From Table 1 and Table 2, it is evident that the AAo and DAo-centered method yields the best results based on the Dice score and is tied with the Vanilla method in terms of Hausdorff distance. However, the ROI-centered method does not perform as well as anticipated.

Method	Average Dice Score	
	Ascending Aorta	Descending Aorta
Bai et al.	0.960	0.953
Hann et al.	0.967	0.966
Biasiolli et al.	0.97	0.98
AAo and DAo	0.976	0.956

Table 3: State of the Art Dice Score comparison - The table illustrates a comparison between the AAo and DAo method and the current state-of-the-art techniques, presenting Dice Scores to three significant figures, except for the method developed by Biasiolli et al., which provides only two.

Table 3 illustrates a comparison of our top-performing method, the AAo and DAo-centered approach, with state-of-the-art results reported by Bai et al. [1], Biasiolli et al. [2], and Hann et al. [4].

Our AAo and DAo-centered approach distinctly

outperforms in assessing the ascending aorta, evidenced by a high Dice Score, while maintaining reasonable accuracy for the descending aorta. In contrast, the data from Biasiolli et al. reveals an unusual pattern; the restriction to two significant digits prevents a definitive analysis of the ascending aorta. This, coupled with an unexpectedly high Dice Score for the descending aorta despite its smaller cross-sectional area, contrary to general expectations and findings from various studies including ours, calls for a nuanced interpretation of the results.
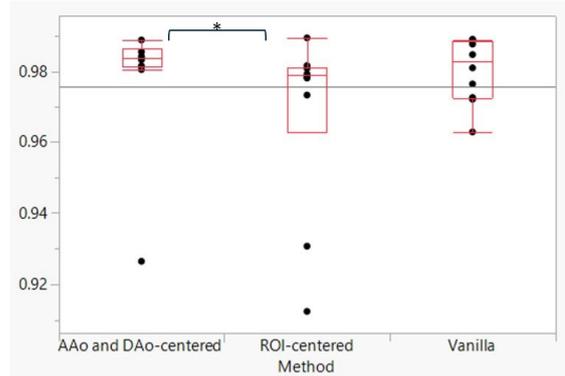
3.2. Results on the dilated aorta test set

In our study, we strive to improve the software's capability to detect stiff and dilated aortas. To this end, we validated our methods using data from the test set including only individuals with large AAos, comprising a substantial number of 2D cine MRI images.
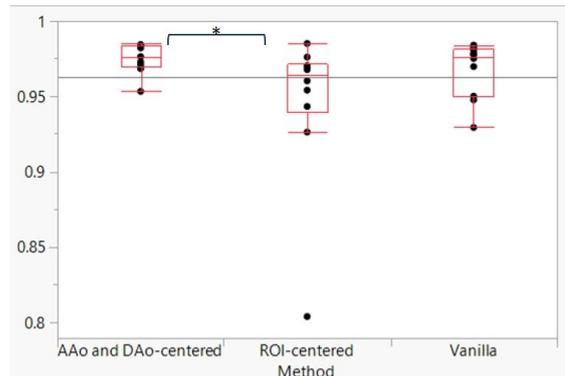
	Dice Score	
Method	**Ascending Aorta**	**Descending Aorta**
Vanilla	0.983 [0.972; 0.989]	0.977 [0.950; 0.981]
ROI	0.979 [0.963; 0.981]	0.964 [0.939; 0.972]
AAo and DAo	0.983 [0.981; 0.986]	0.977 [0.970; 0.984]

Table 4: The Dice Score for the dilated aorta test set is presented in the format Median[First Quartile; Third Quartile].

Table 4 indicates that both the Vanilla and the AAo and DAo-centered methods perform well. However, Figure 5 reveals a significant statistical difference between the AAo and DAo-centered and the ROI-centered methods. Moreover, the AAo and DAo-centered method demonstrates a more clustered and elevated Dice score in the boxplot.

(a) AAo

(b) DAo

Figure 5: AAo and DAo Dice Score - The figure illustrates box-plots of the Dice scores for the Healthy Aorta and Large AAo datasets. The stars marking distinctions indicate significance levels ranging from 0.01 to 0.05.

3.3. Results according to the computed velocity

Our study centrally focuses on analyzing aortic flow velocity through MAE and MSE metrics, leveraging them to directly compare the efficacy of our different methods in assessing arterial health and cardiac output.

The MAE and MSE results in Tables 5 and 6 underscore the AAo and DAo-centered method's advantage over the ROI-centered approach, particularly in AAo flow velocity quantification.

	Mean Absolute Error	
Method	Ascending Aorta	Descending Aorta
Vanilla	2.77 [2.28; 4.34]	**5.69 [3.58; 7.85]**
ROI	3.40 [2.47; 5.47]	8.20 [4.79; 12.46]
AAo and DAo	2.64 [1.75; 3.74]	5.58 [3.52; 7.36]

Table 5: Mean Absolute Error - This table compares the Deep Learning methodologies based on the computation of the blood flow velocity in cm/s in the aorta from the MRI images. The Mean Absolute Error is shown in the format: Median[First Quartile; Third Quartile]

	Mean Squared Error	
Method	Ascending Aorta	Descending Aorta
Vanilla	14.3 [9.5; 45.1]	**56.6 [26.6; 138.4]**
ROI	23.1 [13.0; 87.3]	127.0 [48.3; 287.6]
AAo and DAo	13.4 [5.5; 38.1]	58.9 [24.8; 100.6]

Table 6: Mean Squared Error - This table contrasts various Deep Learning techniques by assessing the computation of blood flow velocity in cm/s from MRI images. The Mean Squared Error is displayed as: Median[First Quartile; Third Quartile].

4. Conclusion

After a meticulous evaluation of three aorta segmentation approaches — the Vanilla method, the ROI-centered method, and the AAo and DAo-centered method — it is evident that the AAo and DAo-centered method excels notably in achieving a high Dice Score for the ascending aorta, surpassing other reliable methods from the state of the art. This method leverages the robust UNet++ architecture and demonstrates moderate precision for the descending aorta. These findings underscore its potential for accurate estimation of flow velocity in the ascending aorta, a critical factor in cardiovascular health diagnostics. The AAo and DAo-centered method stands out as a promising approach in aorta segmentation from dynamic 2D MRI images, offering enhanced precision and efficiency, particularly in the context of ascending aorta analysis.

However, it is important to note the shortcomings identified in the ROI-centered approach, which suffers from information loss, thereby reducing segmentation accuracy.

As we look ahead, further research into the temporal dynamics of cine MRI sequences promises to be a fertile ground for advancements, albeit currently limited by computational constraints. The next concrete step identified is the integration of the AAo and DAo-centered method into the ARTFUN software, a move motivated by the method's high performance and its potential to enhance clinical applications.

In conclusion, this study pioneers a promising pathway for the automated segmentation of the aorta using the UNet++ architecture, setting the stage for significant advancements in the diagnosis and treatment of cardiovascular disorders. The method not only promises enhanced accuracy in cardiovascular diagnostics but also holds the potential to revolutionize patient care by addressing critical health issues such as hypertension and aneurysms.

References

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