IMAGE SEGMENTATION APPLICATION FOR

EFFICIENT 3D RECONSTRUCTION OF

A HYPERTROPHIC HEART

by

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May 4, 2021

ABSTRACT

IMAGE SEGMENTATION APPLICATION FOR EFFICIENT 3D RECONSTRUCTION OF A HYPERTROPHIC HEART

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Hypertrophic cardiomyopathy (HCM) is a genetic condition that causes abnormal thickening of myocardium leading to obstruction of blood flow to the left ventricle outflow tract. To restore adequate blood flow, Septal Myectomy, an open-heart surgery is carried out. Creating a 3D model of the diseased heart using CT scans enables surgeons to visualize the degree of obstruction and develop a surgical plan with minimized risk. To decrease the total time required for 3D reconstruction (about 9.5 – 160 hours) and increase model accuracy, an image segmentation application was developed. The purpose of the application is to decrease the total time of reconstruction by isolating the heart from other anatomical parts (Liver, lungs, ribs, etc.) present in the scans. Upon carrying out 5 reconstruction trials using the application, an average decrease in total reconstruction time

by 4.5 hours was observed. This was due to a significant decrease in manual segmentation required after using the application.

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CHAPTER 1

INTRODUCTION

1.1 3D Reconstruction for Disease Diagnosis

3D anatomical models have been frequently used for educational and illustration purposes by educators and doctors. However, due to the increasing popularity of 3D reconstruction and the advancement of 3D printing technology in the past decade, models reconstructed using medical images are also being used to provide visual aid to surgeons for risk assessment and presurgical planning. In rare conditions where a tumor may be present at an odd or a risky location with minimum visual aid available through images, a 3D reconstruction of the diseased area can be created for preoperative planning. Having a 3D reconstructed part instead of a series of images can give the surgeon a more practical view with regards to performing a surgery and an opportunity for better preoperative planning [8]. Yet, 3D printing life-size anatomical parts can still take hours even with the best printers available, which limits its application to situations where pre-ops are long enough for the reconstruction and 3D printing to be carried out [1].

1.1.1 Heart 3D Reconstruction for Surgical Planning

The heart is a delicate organ responsible for pumping life sustaining fluid continuously throughout the body. While trauma to any other organ in the body may or may not result in immediate death, trauma to the heart can be fatal. Cardiovascular diseases are the leading cause of global mortality, accounting for 1.4 million deaths in developed regions and 5.7 million deaths in developing regions [7]. In addition, most open-heart surgeries are considered high risk due to lack of visibility during surgery [7]. Any surgery carried out with low visibility can result in post-operative complications or failure of the procedure.

To decrease the risk associated with an open-heart surgery, a 3D reconstruction of the heart can be created using medical imaging data obtained from the patient. This model can be used as a means of assessing the degree of obstruction caused by the disease or the overall risk associated with the surgical procedure.

Preoperative planning is an essential part of most surgical procedures. Depending on the type of surgery, a preoperative test or assessment may also be required. Typically, this is done using Chest CT scans for a heart surgery to have a better view of the problem. However, in some cases CT scans may fail to provide enough information regarding the condition and a 3D reconstruction can be of great help. 3D models not only allow surgeons to view the heart from a more practical perspective but to also analyze change in hemodynamic loads or blood flow patterns and assess the level of risk associated with the surgery [1, 6].

1.2 An Application for Rapid Segmentation of the Heart

A major problem regarding most 3D reconstructions carried out using medical images is the total time a reconstruction typically takes. To obtain an accurate model of the heart it can take from a day up a week on average [9]. This is unfeasible especially in a situation where a surgery needs to be performed urgently. Rapid and accurate 3D reconstruction modules can provide surgeons or medical professionals with a 3D model even for cases with a short pre-op time. Since most soft tissue 3D reconstruction procedures involve a lot of manual segmentation due to the presence of unwanted regions, the task becomes tedious and time consuming.

While some expensive reconstruction applications have advanced cropping features that allow the user to remove unwanted regions, most applications only allow for rectangular or circular cropping [1,9]. This project focuses on creating a chest CT segmentation application that allows accurate segmentation of the heart using advanced edge detection algorithms. Since most of the manual segmentation required during a 3D reconstruction process can be attributed to the presence of unwanted regions surrounding the region of interest, adding a preprocessing step to isolate the heart from all surrounding regions to obtain a new set of data with just the heart can significantly cut the amount of manual segmentation required during reconstruction [9].

1.3 Imaging Modality Used

Chest CT (Computed Tomography) scans are used as the primary modality for segmentation due to the following reasons:

- Cheaper in comparison to other imaging modalities.
- Easier reconstruction if used with IV contrast.
- Most used imaging modality for reconstruction by radiologists and surgeons for the heart.

1.4 Assessments

Time and accuracy were taken as the functional requirements to test the application. Different versions of the application were created with each new version including an additional feature or an algorithm update for improved performance of the program and user interactivity. Assessments were carried out to test all versions of the programs and can be found in the Chapter 4.

CHAPTER 2

LITERATURE REVIEW

2.1 Hypertrophic Cardiomyopathy (HCM)

Hypertrophic Cardiomyopathy (HCM) is a genetic condition that causes abnormal thickening of the heart muscles especially in the left atrium and septum region. It occurs due to a mutation in the sarcomere (muscle cells) protein gene and affects contraction of the heart. This abnormal thickening also causes narrowing of the Left Ventricular Outflow Tract (LVOT) which is the pathway for blood to leave the left ventricle and reach other parts of the body through the aorta. The prevalence of HCM globally is 0.2% (1 in 500 adults) and more common in males than females [3].

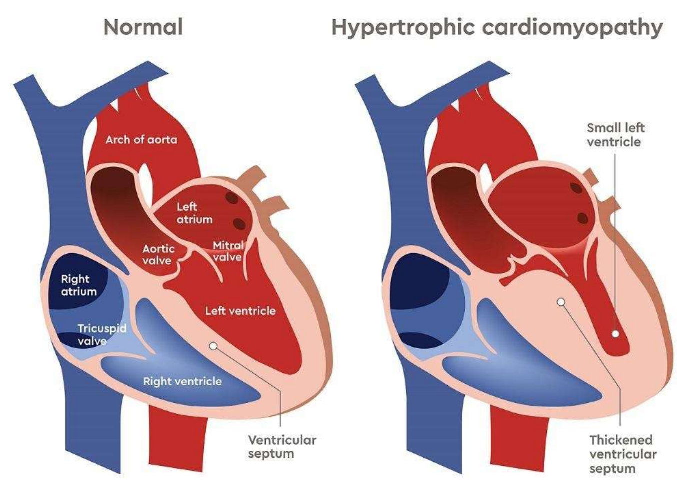


Figure 2.1: Healthy (left) Vs Hypertrophic (Right) Heart (Source: https://s3-ap-southeast-2.amazonaws.com/gc-web/wp-content/uploads/2019/02/30102335/Hypertrophic-cardiomyopathy-image-redesign-021.jpg)

2.1.1 HCM Symptoms

HCM has various symptoms that depend on the level of obstruction cause due to abnormal thickening. Some common symptoms are:

- Shortness of breath
- Fatigue
- Dyspnea
- Chest pain
- Palpitation

In cases of severe obstruction, HCM may lead to diastolic dysfunction, myocardial ischemia, mitral regurgitation, or sudden death [3].

2.1.2 Diagnosis and Treatment

As a genetic disease, HCM can be diagnosed using genetic testing to identify family members having the sarcomere mutation. Echocardiogram, which uses sound waves, is also commonly used as a diagnosis tool to check if the heart muscles are abnormally thick. Electrocardiogram can also be used to test abnormalities in heart rhythms [3].

Initial conditions of HCM can be treated using medications that utilize negative ionotropic agents such as beta blockers, calcium channel blockers and disopyramide. Some common surgical procedures for higher degree of obstruction include alcohol septal ablation or septal myectomy. Alcohol septal ablation is a non-surgical procedure where alcohol is injected into the obstructed area via a catheter to kill or shrink heart muscles.

2.1.3 Septal Myectomy

Septal myectomy is an open-heart surgical procedure performed to reduce muscle thickening that occurs because of HCM [3]. It is a common treatment option for patients when symptoms persist despite regular use of optimal medication. Excess thickening of the heart muscles can cause narrowing of the left ventricular outflow tract which results in obstruction of blood flow from the ventricle to the aorta. This may also result in mitral regurgitation and cause severe damage to the valve.

During septal myectomy, a small amount of muscle is removed from the thickened septal wall in order to widen the outflow tract and restore adequate blood flow [3].

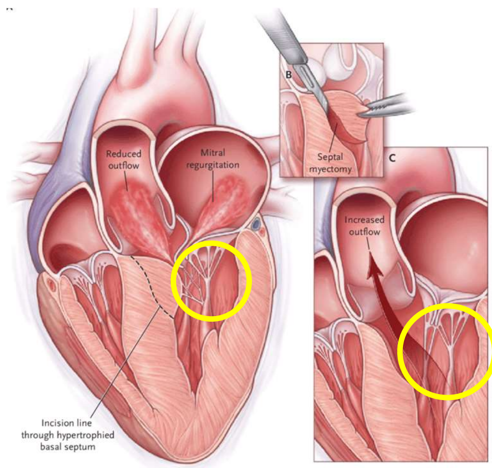


Figure 2.2: Restoration of Blood Flow in A Hypertrophic Heart Using Septal Myectomy. (Source: https://www.researchgate.net/publication/23220831/figure/fig1/AS:601617481093139@1520448193898/Schematic-Diagram-of-a-Patient-Undergoing-Surgical-Septal-Myectomy-Before-the-operation.png)

2.1.4 Postoperative Complications

Like most open-heart surgeries, visibility during septal myectomy is low. In cases where adequate amount of muscle has not been removed due to poor visibility, post-operative complications might occur. The most common post-operative conditions associated with septal myectomy are: Ventricular septal defect, postoperative bleeding, and complete heart block [3].

2.2 Significance of 3D Reconstruction

Researchers have explored using 3D reconstructed models in various clinical and non-clinical trials involving pediatric cardiac surgeries. These models not only allow surgeons to have a tactile experience but also allow for simulations to test surgical or interventional procedures. However, creating an accurate 3D model requires accurate segmentation of the Region of Interest (ROI), the heart in this case. Image segmentation often is a laborious task and requires user expertise and extensive knowledge of anatomy [4,6].

2.2.1 Common Reconstruction Tools

According to a review article on state-of-the-art 3D segmentation software available for 3D reconstruction, the most used tools/features are:

a. Automatic thresholding: This allows the user to segment regions of interest that have a voxel value lying within a certain threshold.
b. Cropping: This allows the user to crop surrounding/unwanted regions to isolate the region of interest
c. Paint/Unpaint: This allows user to manually draw or remove regions from the 3D reconstruction mask.
d. Island removal: This feature allows the user remove small or large floating mask regions created during automatic thresholding.
e. Morphological structuring elements: These are filters that use structuring elements to remove porosity in the mask or irregularities on the mask surface to obtain a solid model.

f. Smoothing: This is a postprocessing step to create a smooth surface on the model for export, 3D printing, assessment, or simulation [4].

2.2.2 Common Imaging Modalities

In the last few decades, the development of various medical imaging modalities has provided doctors an insight to a patient's anatomy without the need for prior surgery. While X-ray and CT (Computed Tomography) are the oldest and the most frequently used imaging modality followed by MRI (Magnetic Resonance Imaging), use of less invasive technology such as Ultrasound and invasive, yet more informative, modalities like PET (Positron Emission Tomography) has also surged in the last few years. Nevertheless, due to significant improvements in imaging quality, resolution, computation power and relatively lower costs, CT and MRI remain the most common imaging modalities used for disease diagnosis.

2.2.3 Limitations

Creating a 3D model from medical images begins by importing a 3D volume of the scans consisting of consecutive 2D axial scans stacked on top of one another. The user then identifies the region of interest and proceeds with segmentation using tools such as thresholding, region growing, etc. The quality of segmentation and the total time it may take depends on factors such as user experience, software used, anatomical region of interest, and so on. For example, bone segmentation does not require a lot of time in most cases as bone is a dense tissue and has a relatively high contrast in most imaging modality. Some commonly used existing software for image segmentation and 3D reconstruction of the pelvic bone can be found in the table below:

Table 2.1: Total Time of Reconstruction for Various 3D Reconstruction Software Used for Pelvic Bone reconstruction (Virzi et al. 2020)

Software	Segmentation time (in hours)	Software	Segmentation time (in hours)
3D Slicer	15	Mango	>20
Anatomist	>25	Medinria	>20
AW Server	>20	MIPAV	>20
Freesurfer	>20	Myrian Studio	9
FSL	>25	Olea Sphere	>20
ImageJ	>25	OsiriX	>20
ITK-SNAP	10	Seg3D	20

In comparison to bone, soft tissues do not provide a striking contrast. They can be difficult to segment without using an IV contrast on patients when collecting imaging data [9]. Although some sophisticated reconstruction software have an advanced cropping feature for removing unwanted regions using wires or curves, most segmentation software only allows for a circular or rectangular cropping around the region. As circular or rectangular cropping still leave some unwanted regions around the ROI, most 3D reconstruction modules require a great amount of manual segmentation to completely isolate the region of interest [4].

CHAPTER 3

METHODOLOGY

3.1 Conversion and Preprocessing

Chest CT scan images in DICOM (Digital Imaging and Communications in Medicine) format were used for segmentation and 3D reconstruction. According to a review on image segmentation methodology for creating patient specific models of the cardiovascular system, CT scan data was the most frequently used modality for 3D reconstruction. This can be attributed to the fact that the cost for CT is lower than MRI, and CT is the mode frequently used for imaging modality for a general diagnosis of the heart [4].

MATLAB App Designer was chosen as the primary platform for developing the Chest CT segmentation application due its superior capability of working with multi-dimensional imaging data and the availability of an advanced image processing toolbox. However, the input data in DICOM format were not compatible as parameters for functions in the image processing toolbox.

3.1.1 Format Conversion

Most image processing functions that are essential for accurate segmentation and isolation of the heart an only be applied to data in the 'double' format. For higher computation power and fast performance, the entire image set was not loaded or stored into the program. One image file was read at a time using the 'dicomread ()' function and converted to a double format using a cast ‘double ()’. The image array was then normalized by dividing all elements in the array with the max value.

3.1.2 Image Preprocessing

To isolate the heart from all surrounding regions, an ‘active contours edge detection’ function was used. However, obtaining desirable results from the algorithm requires preprocessing of the imaging data using various filters used for removing unwanted foreground/background noise from the image.

Figure 3.1: Edge Detection With (Right) And Without (Left) Applying Averaging Filter on ‘Cameraman.Tif’ Image in MATLAB.

3.2 Automatic Edge Detection and Segmentation

After the user selects a Region of Interest (ROI) in the original image, an ‘fspecial’ averaging filter of size 5*5 is applied to the image. The purpose of the averaging filter is to partially blur the image to decrease the level of noise captures by the edge detection algorithm. A morphological structuring ‘disc’ element of size 5 is automatically applied along with an opening operation. The opening operation removes unnecessary extrusions on the edges, to obtain smooth edges.

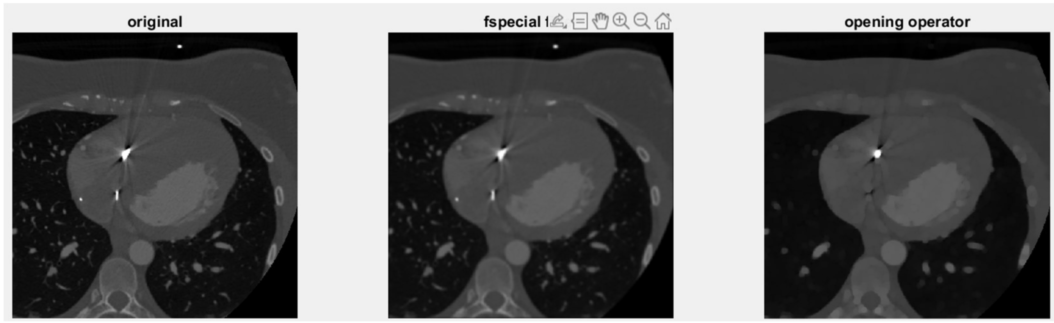


Figure 3.2: Image After Applying ‘fspecial’ Filter Followed by an Opening Operator

3.2.1 Active Contours Edge Detection Algorithm

An active contours edge detection function was applied on the processed image by allowing the user to draw a circular boundary around the regions of interest. A total of 450 iterations were applied on each image for accurate detection of the heart contour. With each iteration, the boundary of the circular or hand drawn region on interest shrinks inward until it finds a prominent edge.

3.2.2 Binary Masking for Segmentation

The contour of the heart created by the edge detection algorithm was automatically saved as a binary image file which was then used to obtain the final binary mask by using an ‘AND’ operator between the counter and the original ROI selected by the user. This binary mask is then applied on the original image to obtain the isolated version of the heart. This isolated image is then attached to a blank image of the original image size using 2D matrix operations just in case a cropping operation was used. The result obtained was converted into ‘uint16’ datatype and written as a .dicom file. In order to make sure that all isolated images fall under the same series, a new dicomuid was created and used for all images in a given series.

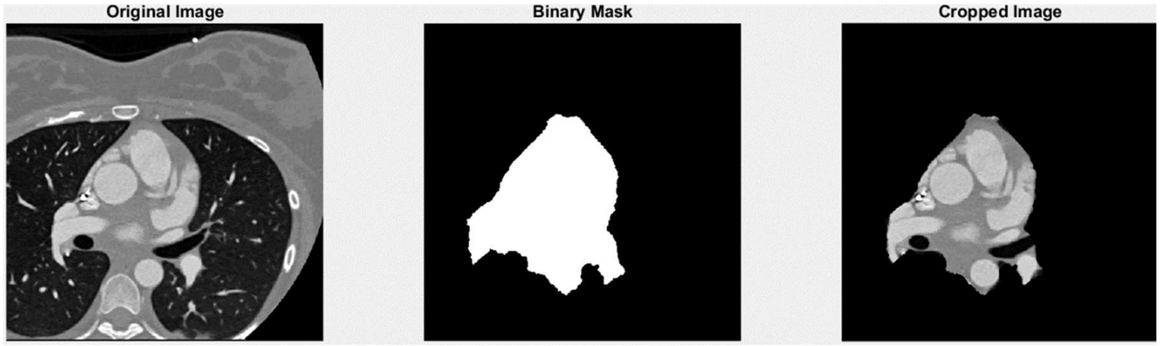


Figure 3.3: Original Image (Left); Binary Mask Obtained from Edge Detection Algorithm (Center); Result After Applying Binary Mask on the Original Image.

3.3 Graphical User Interface

An interactive Graphical User Interface (GUI) with multiple functionalities for a seamless segmentation was created using a guided object-oriented programming interface on the MATLAB App Designer.

3.3.1 Display Axes

A total of 3 UI Axes were implemented into the interface: 1) to display the original image and provide an interface for selecting the Region of Interest (ROI) titled ‘Primary Image’, 2) to display a histogram-equalized version of the image titled ‘Equalized Image’, and 3) to display the result after segmentation titled ‘Image with Mask’. After the user loads a file containing DICOM images, the original image is first viewed in the ‘primary Image’ UI axis. If the user chooses to apply histogram equalization on the image to increase contrast before segmentation, an image with high contrast appears under the ‘Equalized Image’ UI axis. Finally, after the user selects an ROI, image of the segmented heart is displayed in the ‘Image with Mask’ UI axis.

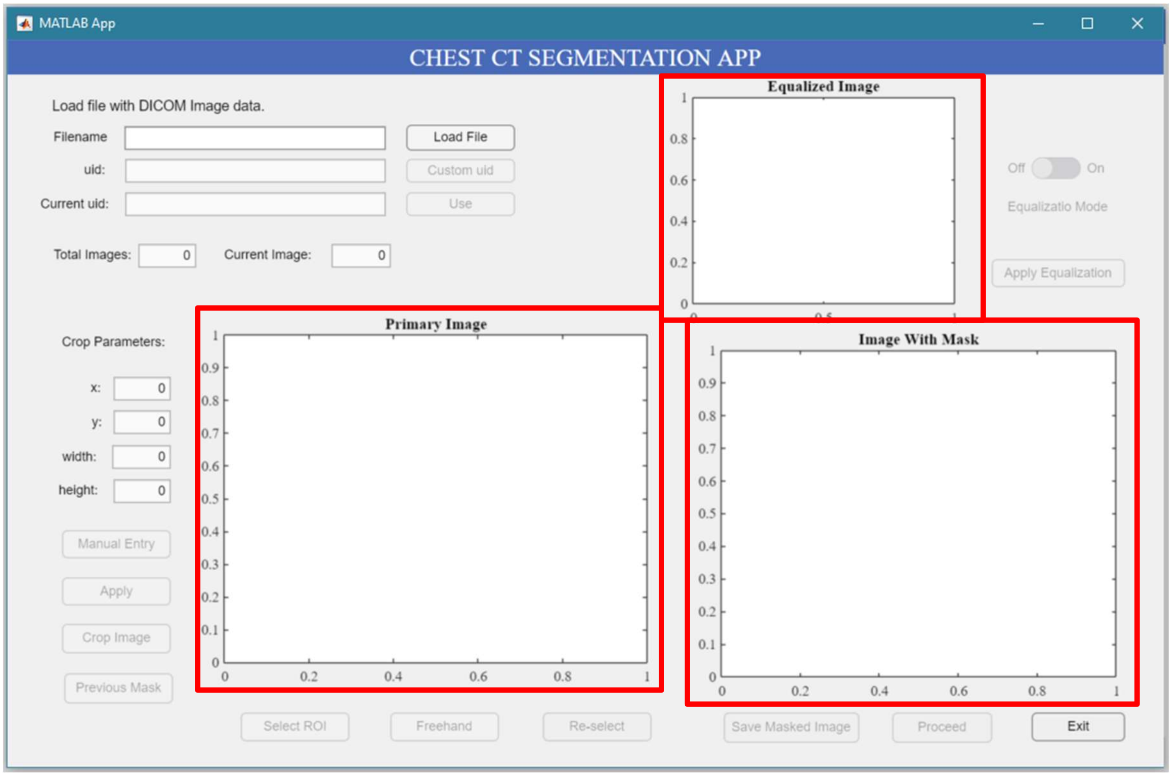


Figure 3.4: UI Axes: Original Image (Bottom Left), Histogram Equalized Image (Top Right), Final Isolated Image (Bottom Right).

3.3.2 Program Features

The following user interactive components were integrated into the UI to provide the user with a user-friendly environment and features that allow for easy segmentation:

Table 3.1: List of Features Integrated into the Application GUI

S.N.	Component Name	Type	Functionality
1.	Load File	Button	Allows the user to enter a filename containing a single series of Chest CT scan data for segmentation.
2.	Custom UID	Button	Every series of DICOM images has a uid associated with it. This feature allows the user to enter a custom UID.
3.	Use	Button	This allows the user to use the current uid associated with the series instead of a custom uid.
4.	Total Images	Edit Field	Displays the total number of images in the series.
5.	Current Image	Edit Field	Displays the current image number being segmented.
6.	Crop Parameters	Edit Field	Displays x, y, height, and width of the rectangular crop function, if used. Also allows for entering crop parameter data if 'manual entry' is pressed.
7.	Manual Entry	Button	Allows user to manually enter crop parameters
8.	Apply	Button	Allows user to apply manual crop parameters to create a rectangular crop around the image.
9.	Crop Image	Button	Allows the user to hand draw a rectangular region of interest to crop an image.
10.	Select ROI	Button	Allows the user to select a circular region of interest displayed on the 'Primary Image' axis to create a circular boundary as the starting point for the active contours edge detection algorithm.
11.	Freehand	Button	Allows the user to freely draw around the region of interest on the image displayed on the 'Primary Image' axis to create a starting point for active contours edge detection algorithm.
12.	Re-select	Button	Allows the user to remove last ROI drawn and redraw around the region of interest.
13.	Equalization Mode	Switch	Displays histogram-equalized version of the image on the 'Equalized Image' axis. Applying histogram equalization can increase efficiency of edge detection in some scenarios where the boundary of an object cannot be distinguished easily.
14.	Apply Equalization	Button	Applies equalization to the image and uses equalized version of the image for segmentation.
15.	Save Masked Image	Button	Saves the final image obtained through the edge detection algorithm.
16	Proceed	Button	Procced to the next image.
17.	Previous Mask*	Button	Use binary mask created for the previous image on the current image.
18.	Exit	Button	Shut down application.

*This can be useful during medical image segmentation as consecutive images tend to have very similar or same regions of interest.

3.3.3 Program Assessment

The goal was to decrease the total time of segmentation, increase accuracy of the edge detection algorithm, and make the program more interactive and easier to use. To test the program, a single set of chest CT scan data was taken and segmented using the application. The total time of segmentation, the total number of breaks, and the duration of each break were recorded. The accuracy of the edge detection algorithm was measured by comparing the boundary of the heart in each axial segmented scan with the boundary of the heart in the original scans.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Program Versions

A total of seven versions of the program were created throughout the iterative assessment process, with each version receiving an update of features or change in image segmentation algorithm.

4.1.1 User Interface

The user interface was created on a MATLAB App Designer Window and the application was named as 'Chest CT Segmentation Application'.

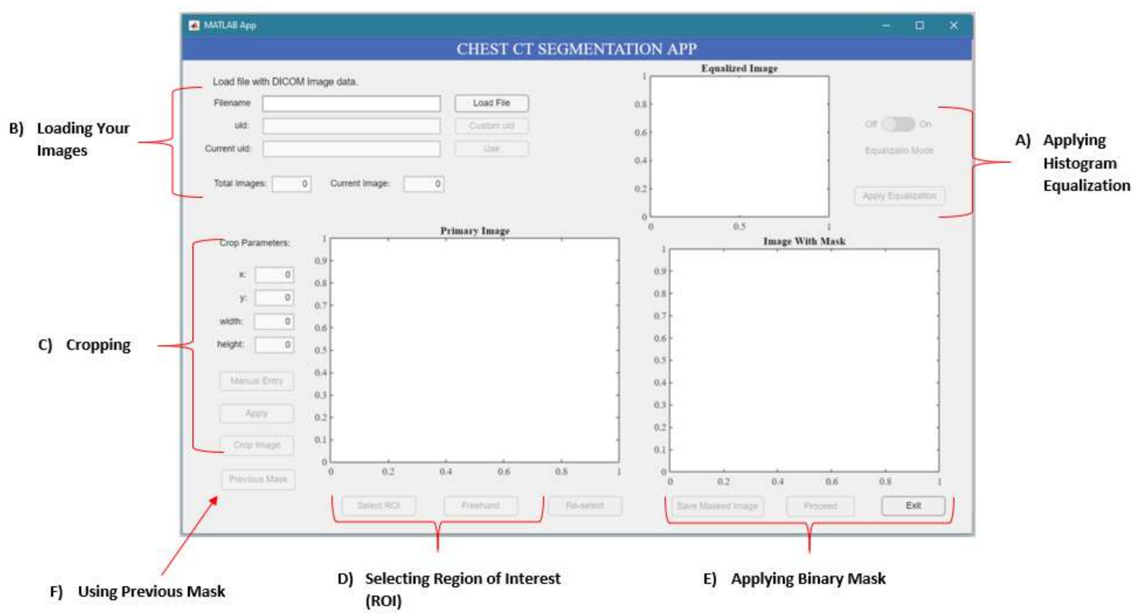


Figure 4.1: Application User Interface

The features for uploading DICOM series data and selecting a unique identifier number were integrated into the top left part of the window. The 'Primary Image' axis, which will display the current CT scan image for segmentation, was integrated at the center of the window towards the left. On the left of the ‘Primary Image’ axis, the user can find all features related to cropping and the button for applying the last ROI onto the current image. Right under the primary image axis, features for selecting the region of interest (circular or hand drawn) are located. The histogram-equalized image can be viewed on the top right of the window under the ‘Equalized Image’ axis after enabling equalization mode. The ‘Image with Mask’ axis displays the final image with the region of interest isolated from the rest of the scans and is found in the bottom right part of the window. Features that allow the user to save the final image and proceed to the next scan can be found under the bottom right axis.

4.1.2 Update Features

Iterative assessment was carried out after each version of the program and potential problems and bugs were identified. The algorithm was modified as necessary using error handling statements and redundant variables/operations were removed for faster execution. A summary of assessment of the last five versions of the program can be found in the table below:

Table 4.1: Program Iterative Assessment Summary

S.N.	Segmentation Time	No. of Breaks	Break Duration	Problem(s) Encountered	Changes /Improvements
V 3	~ 3 hours	4	10 mins	Scans in the caudal part of the heart could not be segmented with precision.	Freehand option was added.
V 4	~ 2.5 hours	3	15 mins	Images segmented using the freehand option had a high error at the boundary.	A structuring element of size 5*5 was used to dilate the binary mask and reduce error at boundaries.
V 5	~ 2.3 hours	2	20 mins	The “Proceed” button had to be clicked for each image before clicking the ‘Save’ button making the process tedious.	Proceed button was removed and its functionality was restored into “Save Mask”.
V 6	~2 hours	2	15 mins	Lag in the program while using the previous mask feature multiple times.	Program was evaluated thoroughly, and duplicate/unnecessary global variables and statements were removed.
V 7	~1.7 hours	2	15 mins	Figure window kept popping up after using the circular ROI feature.	Algorithm for the ROI callback function was adjusted for better connection of the parent UI.

4.2 3D Reconstruction

4.2.1 Segmentation Time

The maximum time for segmentation was found to be four hours without breaks and 4.75 hours with breaks, whereas the minimum time for segmentation was 1.7 hours without breaks and 2.2 hours with breaks. The average number of breaks taken per trial was 2.8 and the average duration of a break was found to be 14.5 minutes.

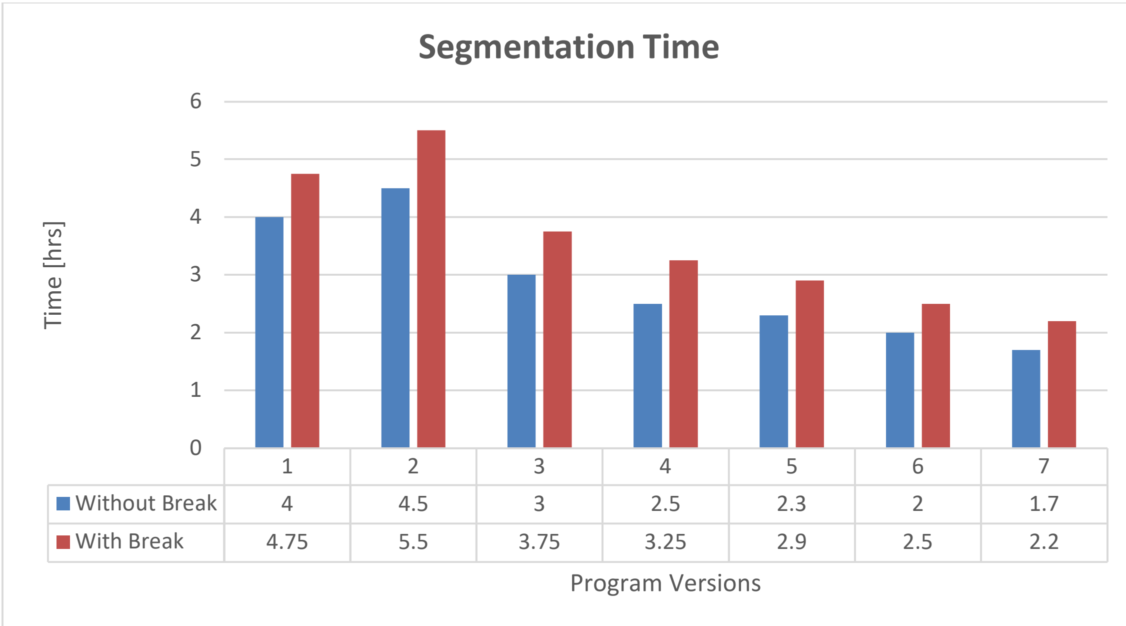


Figure 4.2: Segmentation Time for Different Versions of the Program

The average decrease in segmentation time per trial was 0.38 hours without the user taking breaks and 0.42 hours with breaks. The maximum decrease in segmentation time by 1.75 hours was found after updating the program from version 2 to version 3. This can be attributed to the addition of the 'Last ROI' feature into the program and removal of mandatory rectangular cropping. Since consecutive CT scans tend to be very similar, the 'Last ROI' feature allows the user to automatically select the ROI that was drawn in the previous image. Due to this, the user does not have to draw an ROI on every single image. The rectangular cropping was also made optional as all images do not require a rectangular crop to produce efficient results from the active contours edge detection algorithm.

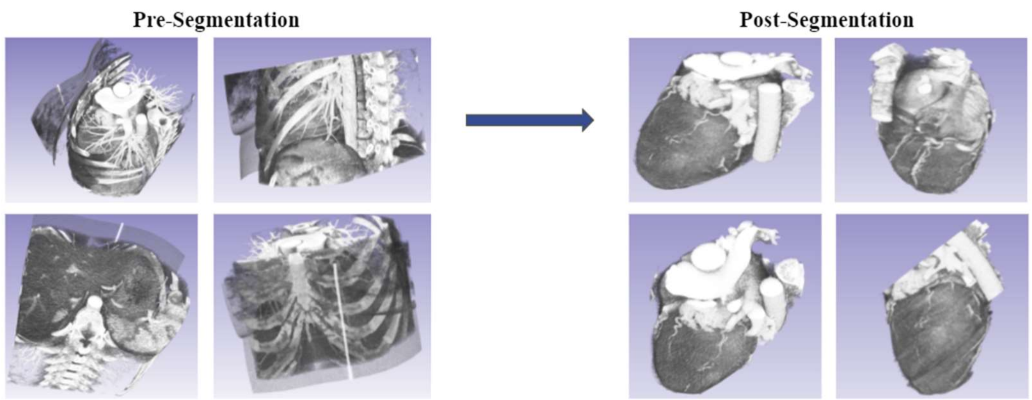


Figure 4.3: Results After Segmenting a Single Set of Chest CT Scan Data

4.2.2 Reconstruction Time

For the final assessment of the program, a total of six heart models were created using 3D reconstruction from which three used the original unaltered version of the scans (Figure 4.3 left) and the other three used the new set of scans where the heart had already been isolated (Figure 4.3 right). The total time of 3D reconstruction was recorded for all six models by also including the time taken for the segmentation of models that used the new scans.

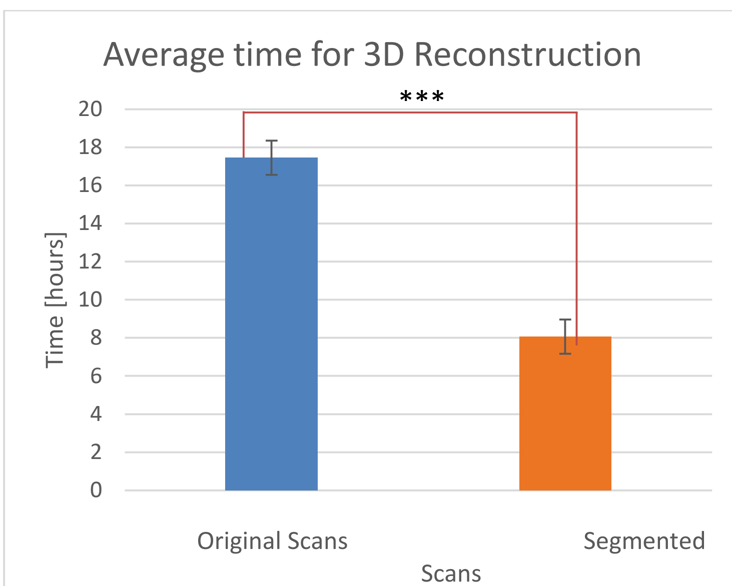


Figure 4.4: Average Total Time for 3D Reconstruction for Original Vs Segmented Scans

Based on the p-value (0.001), results showed that the average time for 3D reconstruction for the original version of the scans was 9.5 hours more than for the segmented scans. With this we can conclude that there is a significant different between the time for 3D reconstruction for original vs segmented scans. It is also important to note that the total time for 3D reconstruction using segmented scans also includes the time taken for segmentation using the app.

CHAPTER 5

CONCLUSION

3D reconstruction of anatomical parts using medical images can greatly aid doctors in disease diagnosis and preoperative planning. However, due to a lack of a general workflow protocol, reconstruction remains a laborious task and becomes unfeasible in a clinical setting. The large amount of time taken for 3D reconstruction limits its application to surgical procedures that have a longer pre-operative time. Through iterative assessments, the amount of manual segmentation required to remove the effect of unwanted surrounding regions while thresholding was identified as the major reason behind extended reconstruction time for the original scans. Though many reconstruction software provides advanced cropping functions that allow the user to crop many layers at once, they are still limited in their ability to crop out irregular objects such as the heart [2,9].

Therefore, creating an application that allows the user to segment each axial image from CT scan data by providing features that make the process seamless can significantly decrease the total time of 3D reconstruction. After the user selects a Region of Interest (ROI), the algorithm automatically applies the active contours edge detection algorithm and saves the isolated heart as a new CT scan data. In addition, the final set of Chest CT scan data produced by this application can be used with any 3D reconstruction software that accepts images in DICOM format [5,10]. Moreover, the workflow pipeline used for precisely segmenting the heart from its surrounding regions can be applied to other parts of the body, such as the kidney, pancreas, liver, etc., by making any modifications necessary. By conducting further research, the application's ability to segment a heart from its surrounding regions can be extended to create a custom annotation tool for labeling medical images for machine learning applications [10].

APPENDIX A

CHEST CT SCAN APPLICATION COMPLETE GUIDELINES/PROTOCOL

Chest CT Segmentation Guide

The chest CT segmentation app was created using the MATLAB app designer tool. This application provides the user with a friendly interface to segment chest CT scan images and create a completely new series a Unique Identifier(uid). Unique Identifiers are a series of numbers unique to each set of medical imaging data in DICOM format.

Note: The Chest CT Segmentation app is exclusively created for segmentation of medical images in DICOM format (. dcm extension). The program works best with axial scans.

Axial Chest CT scan example:

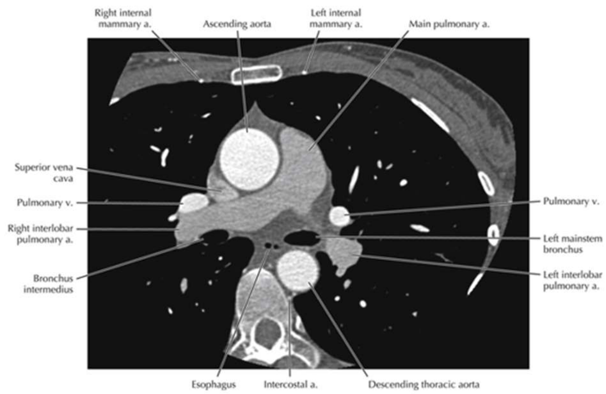


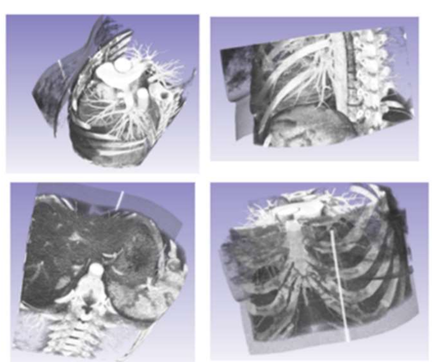
Image obtained from https://radiologykey.com/cardiac-anatomy-using-ct/

Program Purpose

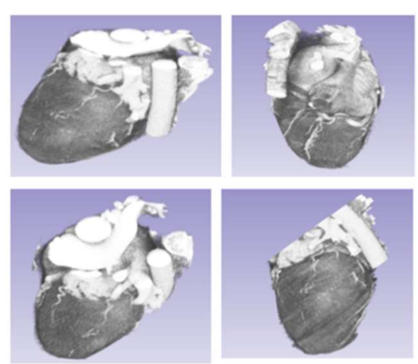
Oftentimes during a 3D reconstruction process, the presence of unwanted anatomical features can decrease the efficiency of automatic thresholding and significantly increase the amount of manual segmentation required. While most programs do allow for a rectangular/circular crop, unwanted regions around the object of interest may remain and interfere with the efficiency of the overall 3D reconstruction.

The chest CT segmentation app gives the user the liberty to remove all unwanted regions prior to uploading the scans to a 3D reconstruction program. An example of the final product after using this application is shown below:

Before preprocessing

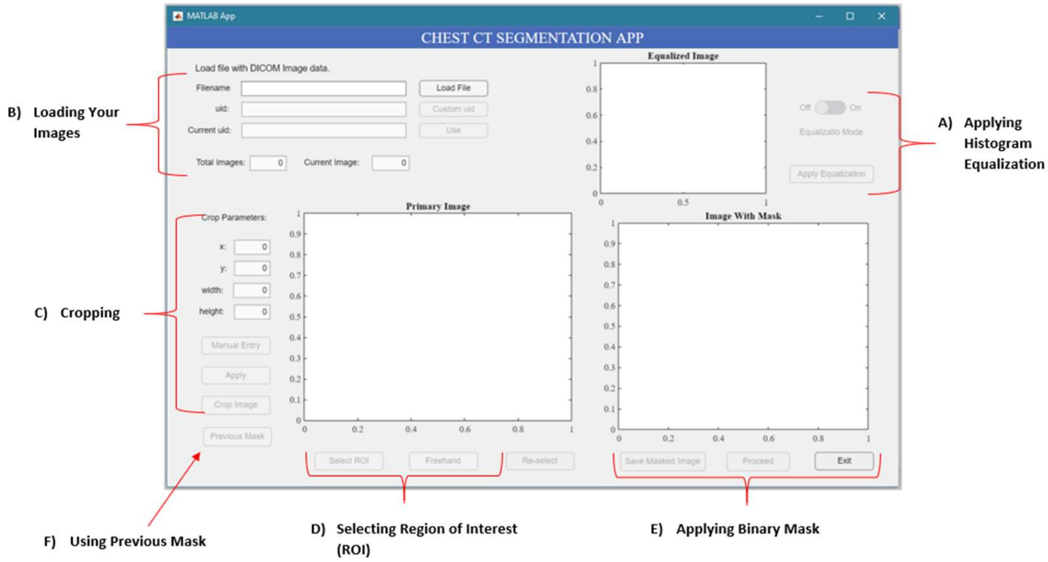


After preprocessing



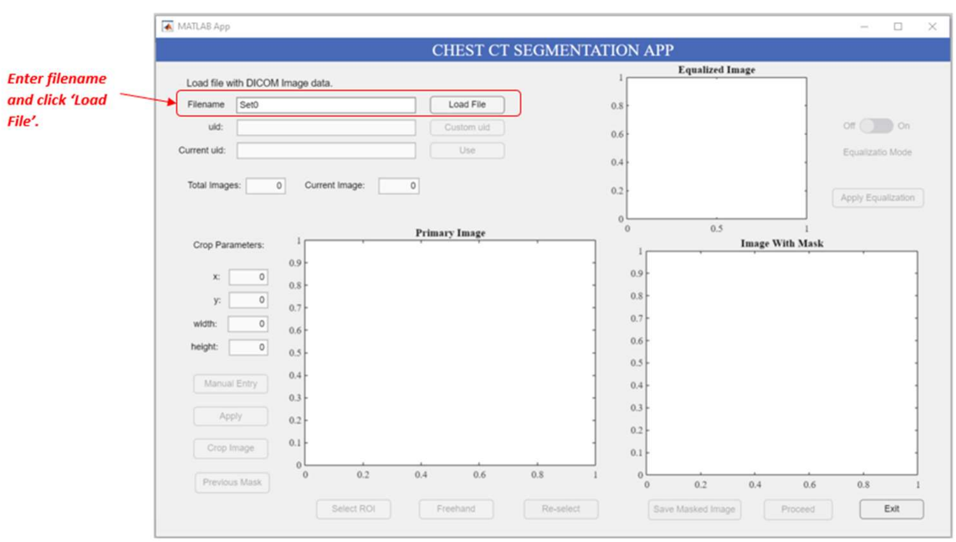
Application UI

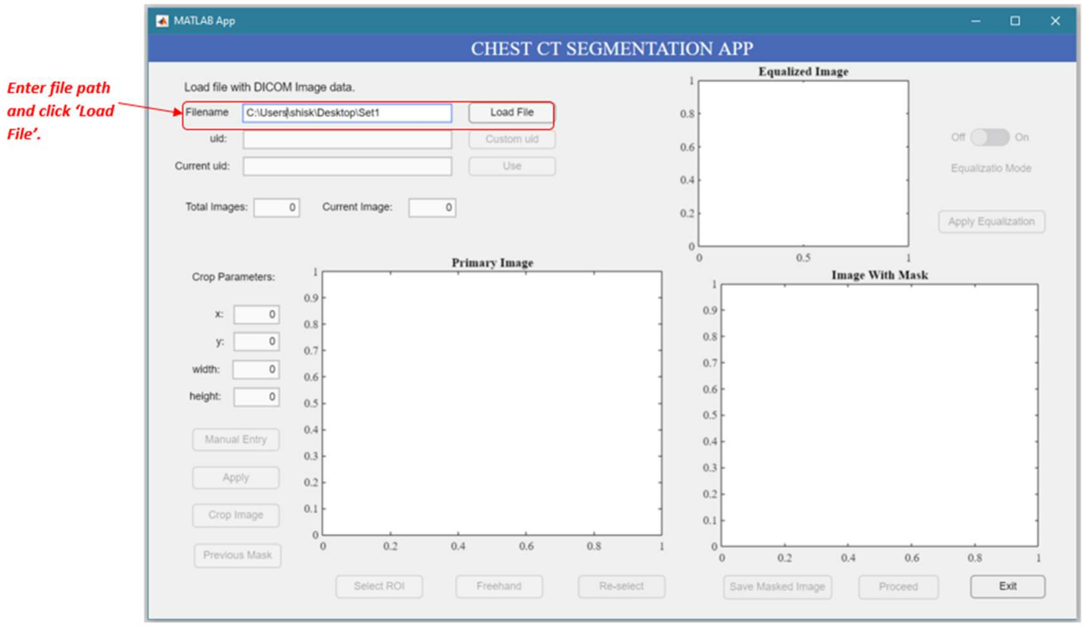
The application exhibits a simple interface with self-explanatory features designed to guide the user through a seamless segmentation experience. **To install the app, open MATLAB first and then click on the application file. On being asked whether you want to install the file, click 'install'. The application will appear under 'APPS'.**



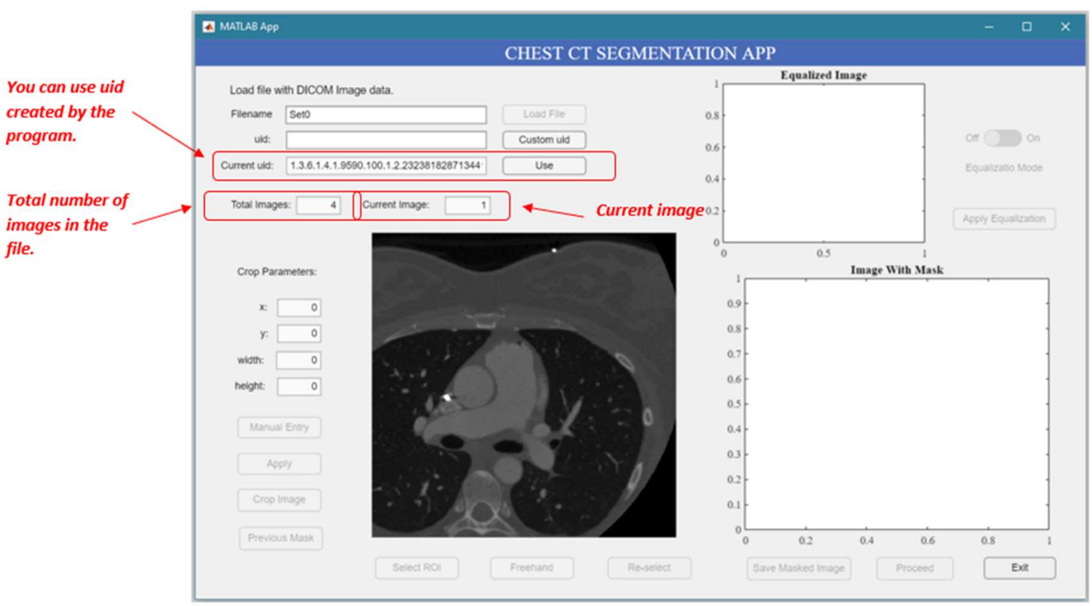
A) Loading Your Images

1. To load your images, simply enter the filename and press the 'Load File' button if the file is in the same folder as your MATLAB interface.
2. If your files are in a different location, enter the file path instead.
3. Note: You DICOM series of images MUST be placed in a folder and the same folder name must be used to load your files.

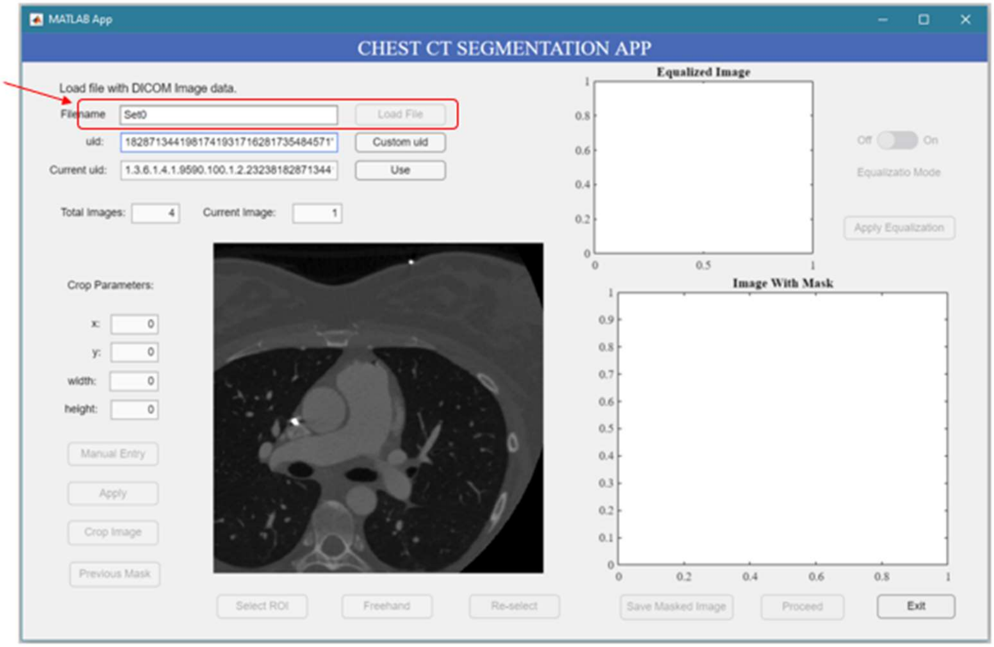




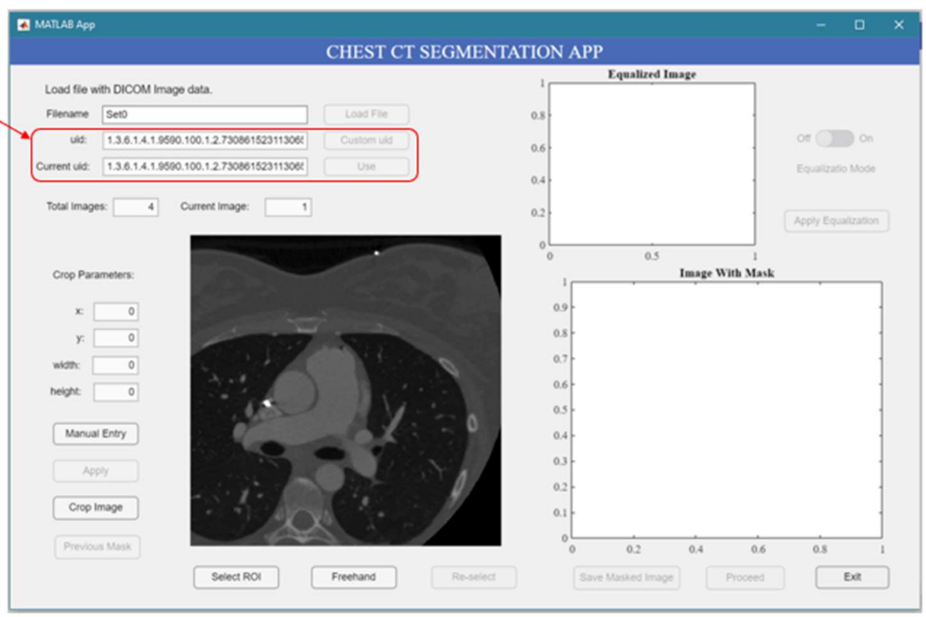
4. After loading a file, you can either use the series uid created by the program or enter a custom uid.
5. *Note: Every time you load a new folder, the images get associated with a newly created uid.*
6. Using custom uid allows you to write images as a part of the same series. This can be useful while working with file containing many pictures as segmenting all images in one sitting may be unfeasible.



Or enter your custom uid.



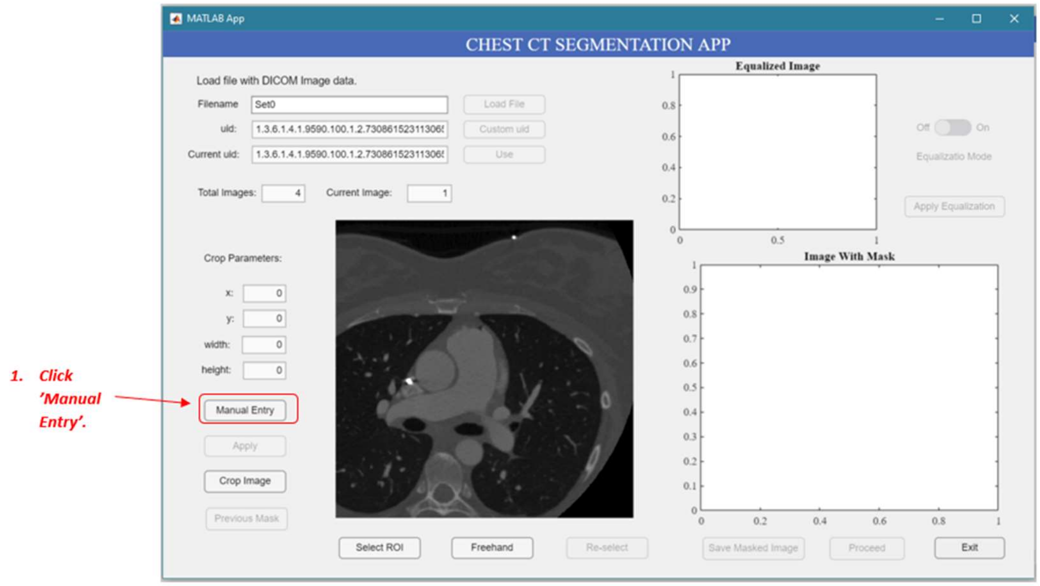
If you choose to enter your custom uid, the current uid will be updated to match your uid.



B) Cropping

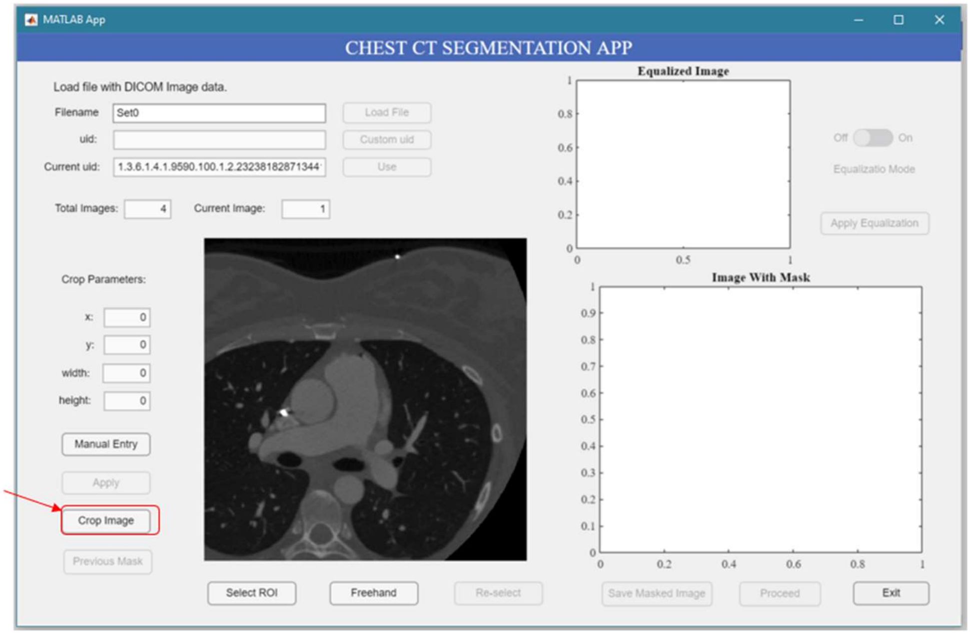
Cropping the images to get rid of black regions towards the boundary can be beneficial especially in cases of images in which histogram equalization must be done for accurate edge detection.

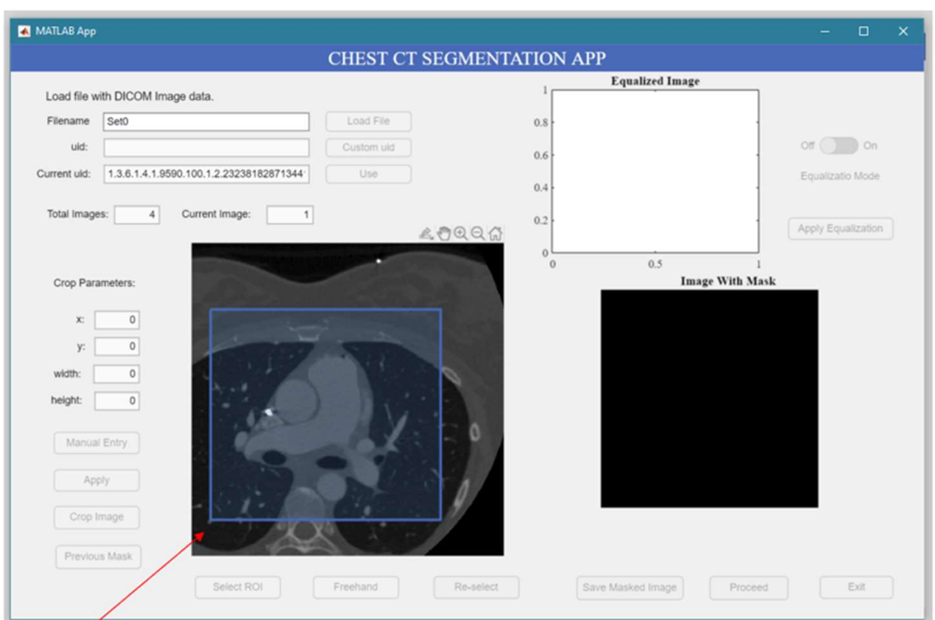
1. To create a rectangular crop on the image, click 'Manual Entry' and enter coordinate points (x, y, width, height) of the rectangle. After entering all four values, click 'Apply'.



2. You can also crop by clicking ‘Crop Image’ and drawing a rectangular region directly on top of the image.

1. *Click ‘Crop Image’.*

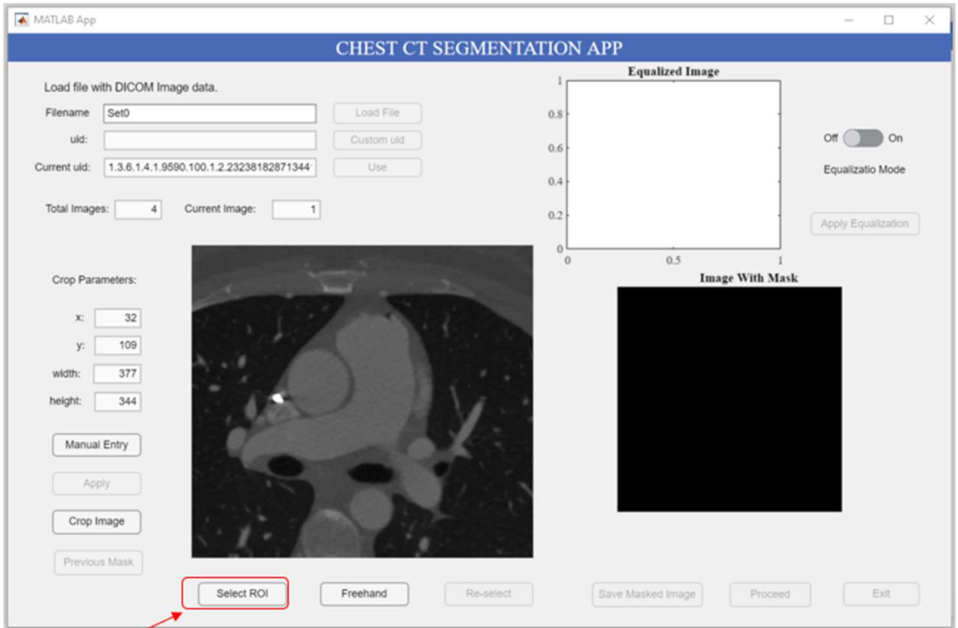




2. *Draw rectangular region.*

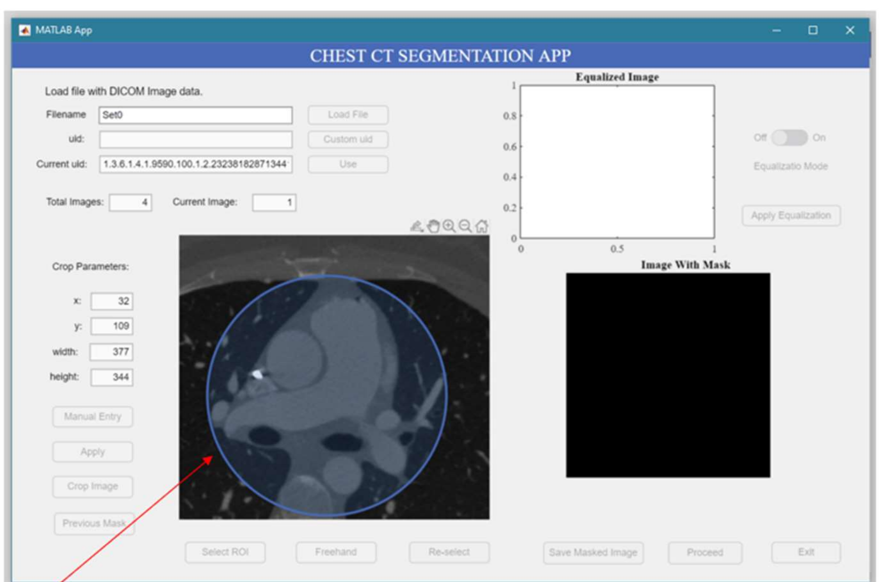
C) Selecting Region of Interest (ROI)

1. After cropping, click 'Select ROI' to draw a circular region of interest on top of the image.



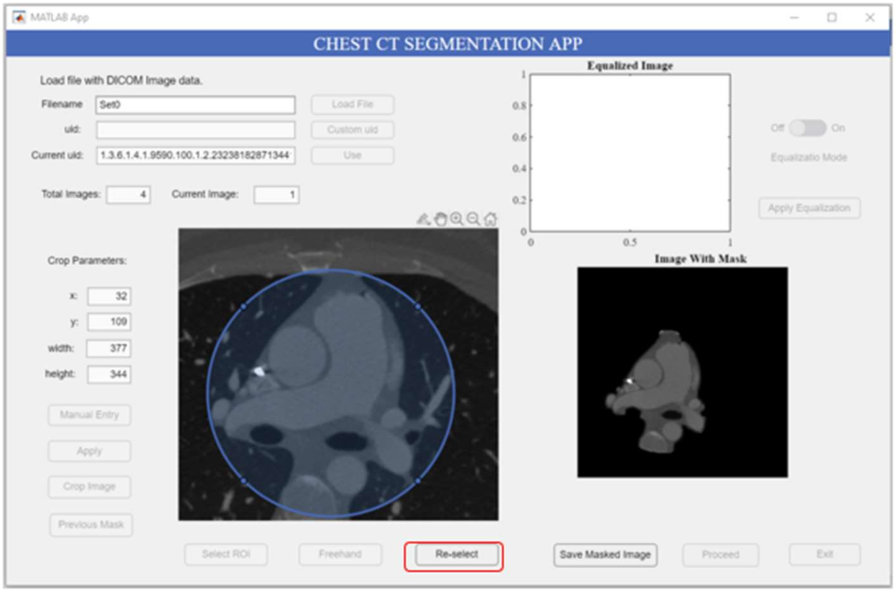
1. Click 'Select ROI'.

2. The circular ROI drawn will behave as a starting boundary for active contours edge detection algorithm. Region inside the circular ROI will be saved and everything outside the ROI will be eliminated.



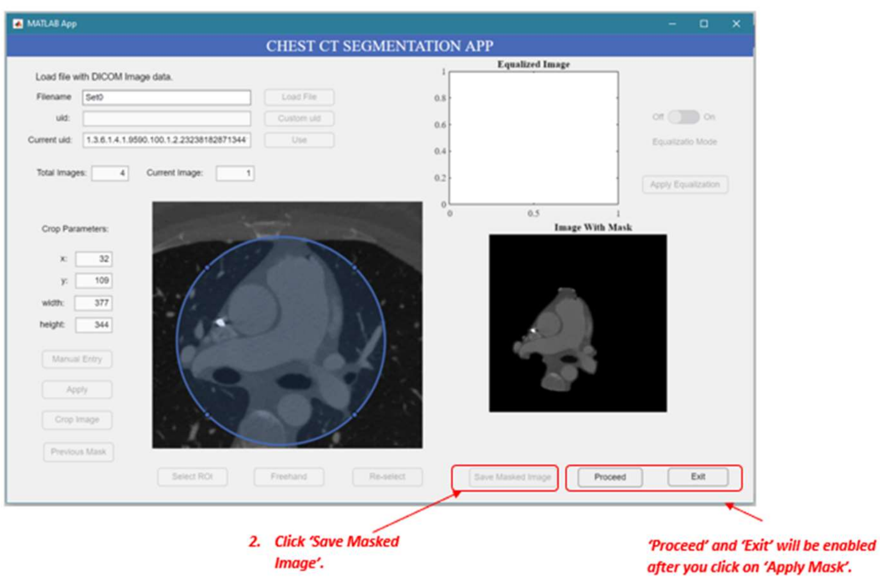
2. Draw circular ROI.

3. Click ‘Re-select’ to remove the previous ROI and draw a new one.



D) Apply Binary Mask

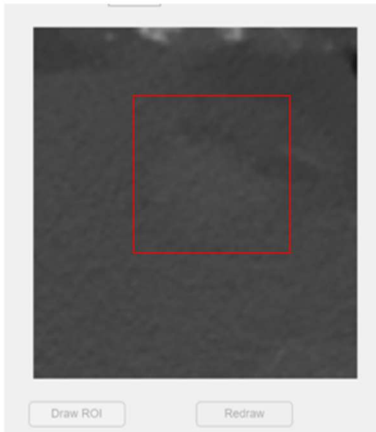
1. Once the circular ROI has been drawn, the isolated image will appear under ‘Image with Mask’. Click ‘Save masked Image’ to save this image.
2. Click ‘Proceed’ to move to the next image or “Exit’ to close the program.



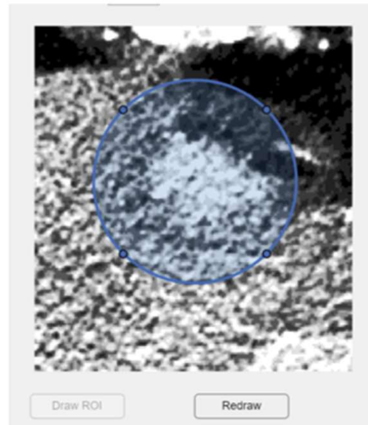
E) Histogram Equalization

Applying histogram equalization can increase efficiency of edge detection in some scenarios where the boundary of an object cannot be distinguished easily.

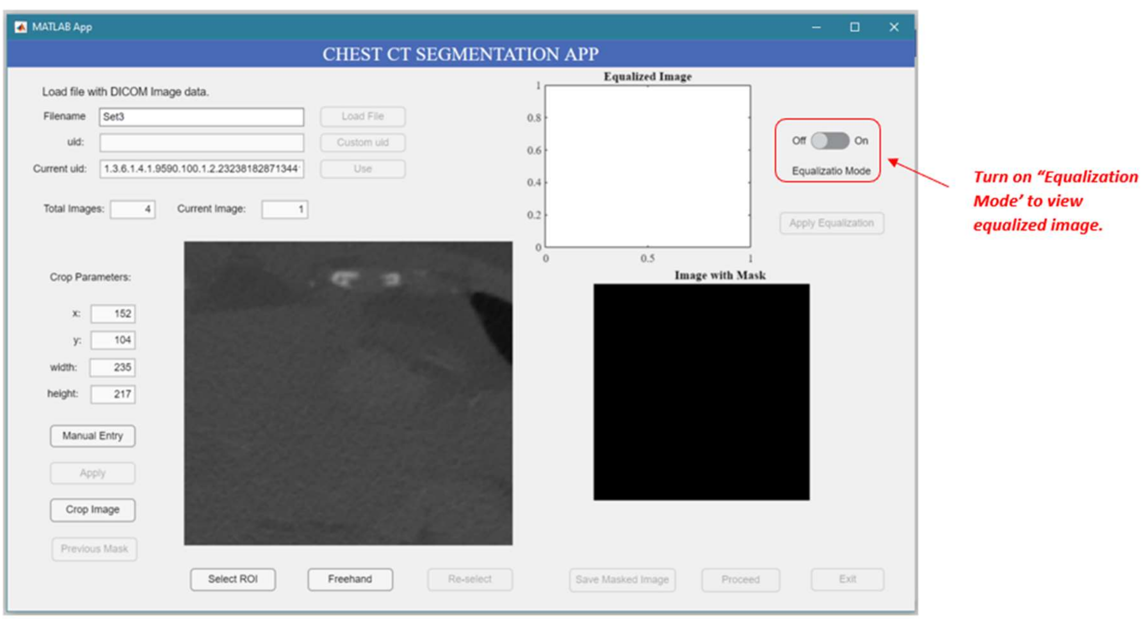
Before Equalization



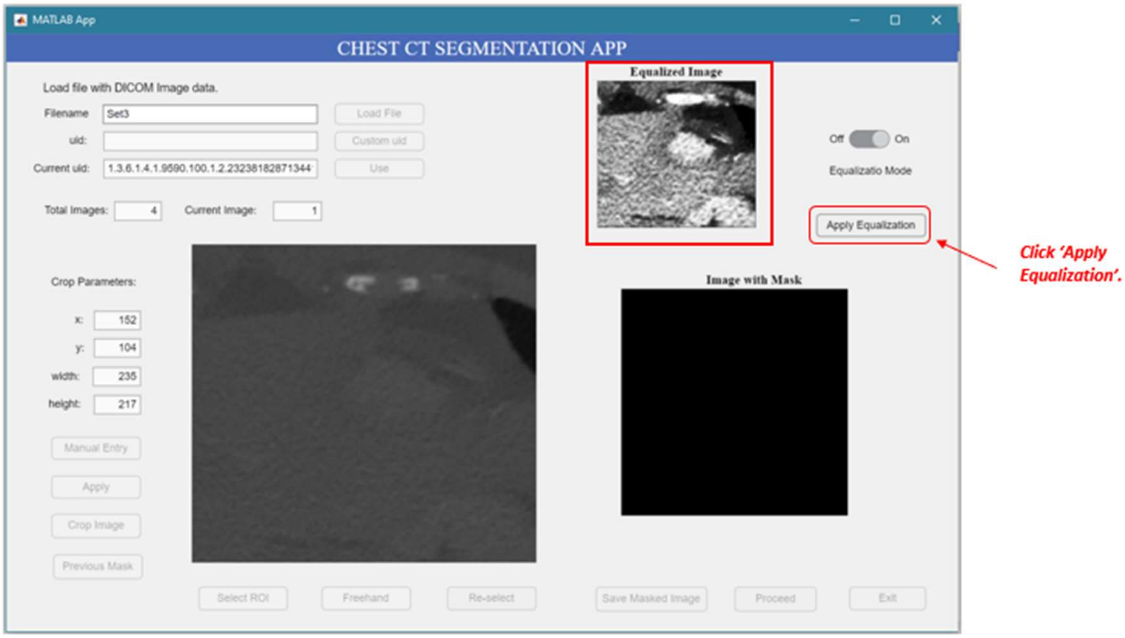
After Equalization



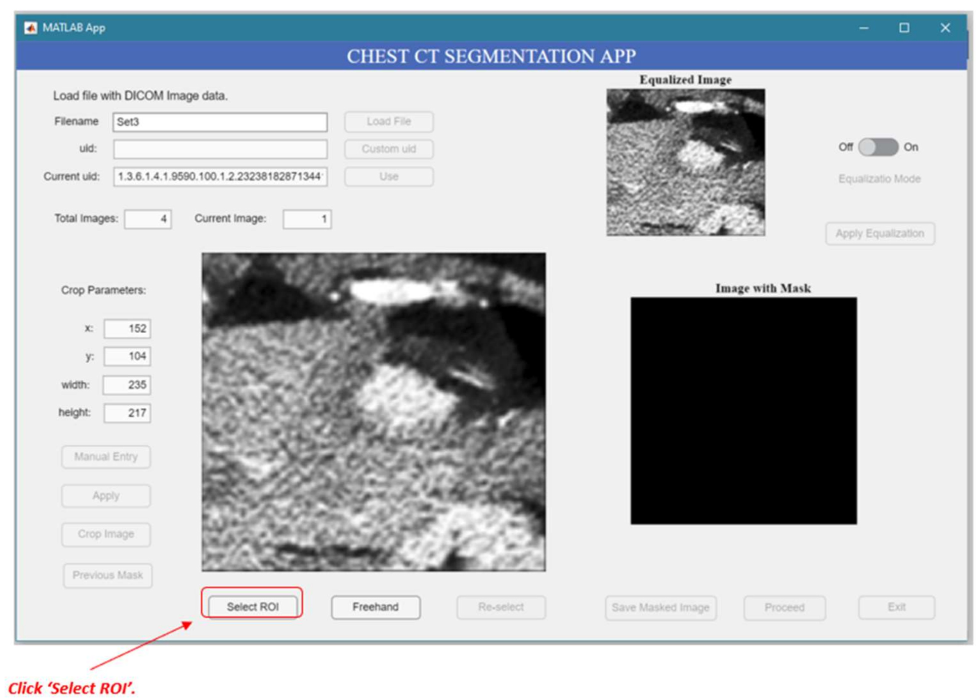
1. The histogram equalization switch will be enabled after the image has been cropped.

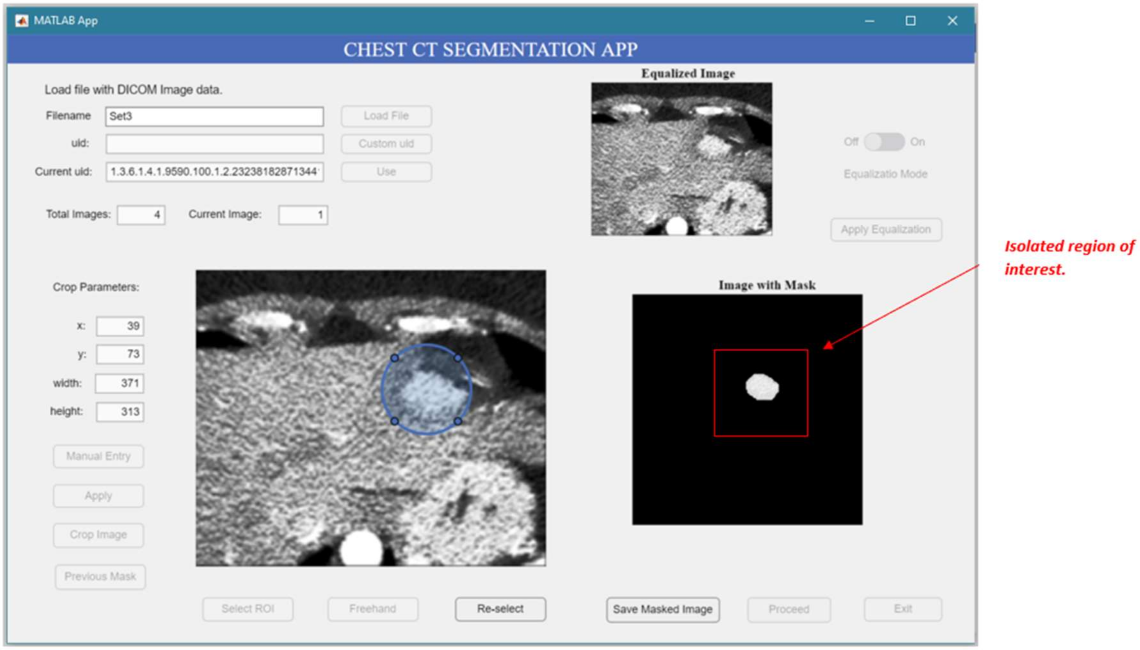


2. The equalized image can be seen under ‘Equalized Image’.
3. Click ‘Apply Equalization’ to use equalized image.



4. Click ‘Select ROI’ to draw circular region of interest.

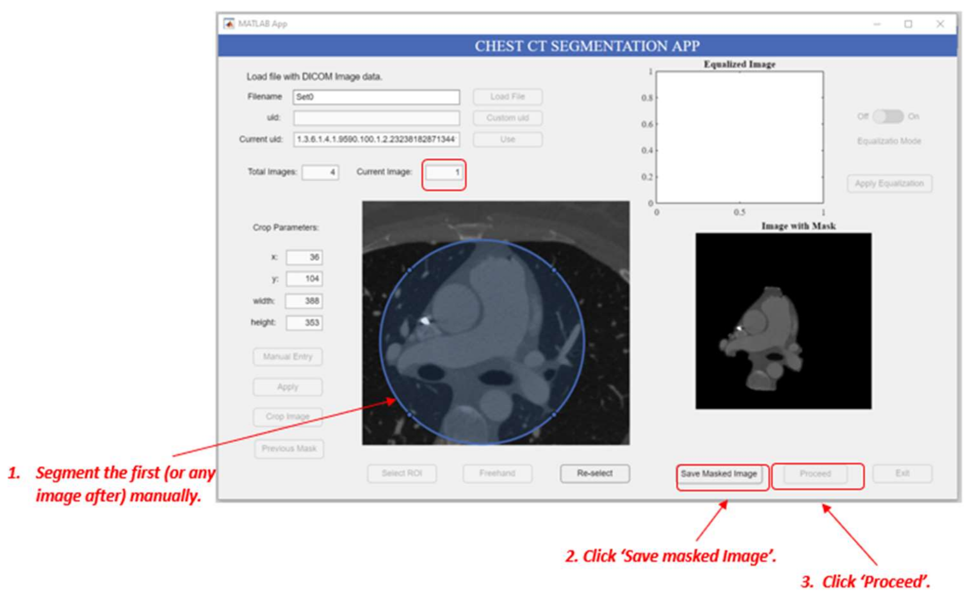


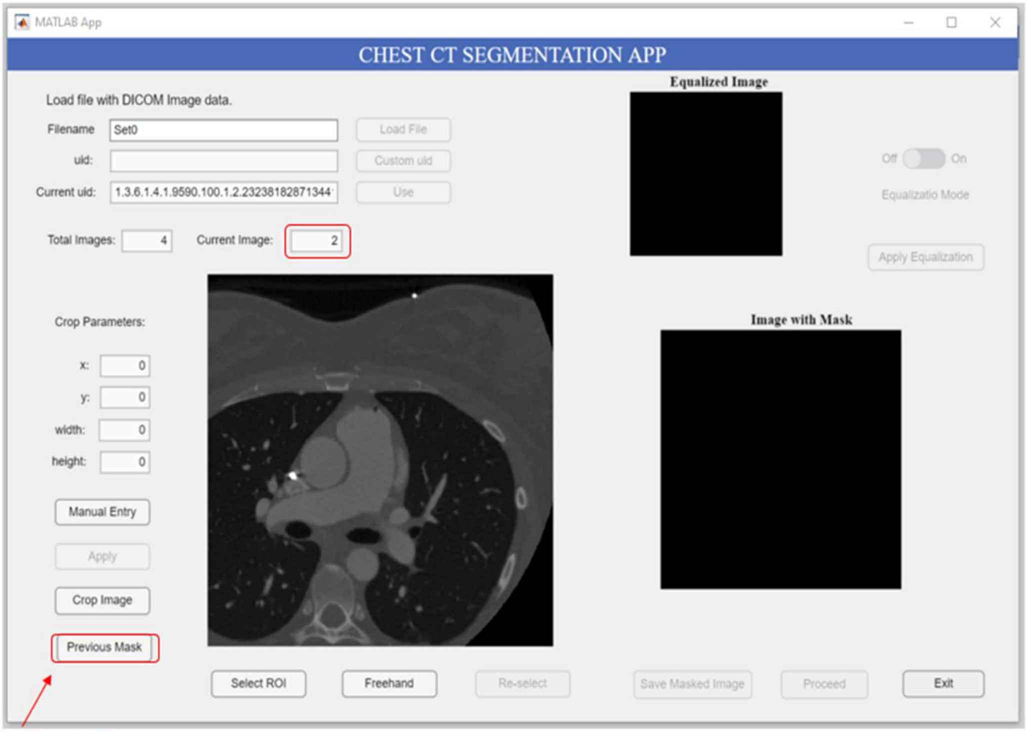


F) Using Previous Mask

The 'Last ROI' button can be used to apply the last binary mask to the current image. This can be useful during medical image segmentation as consecutive images tend to have very similar or same regions of interest.

1. After clicking 'Proceed' the program will load the next image. Click 'previous Mask' to directly obtain the segmented image without having to crop or draw circular ROI.

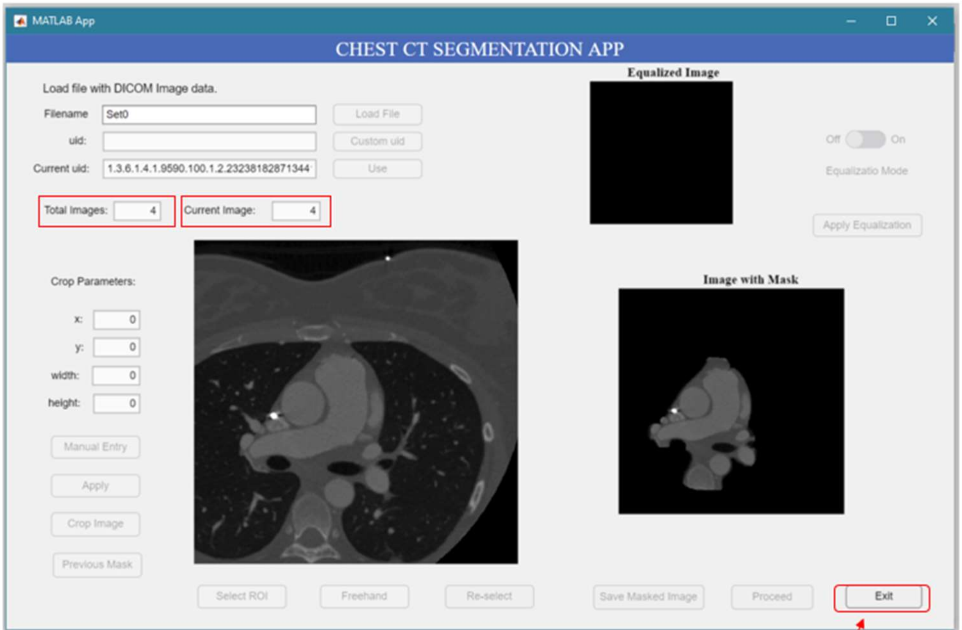




4. Click 'Previous Mask'.

Binary mask from last image applied to current image.

2. After all the images have been segmented, the user will be prompted to exit.



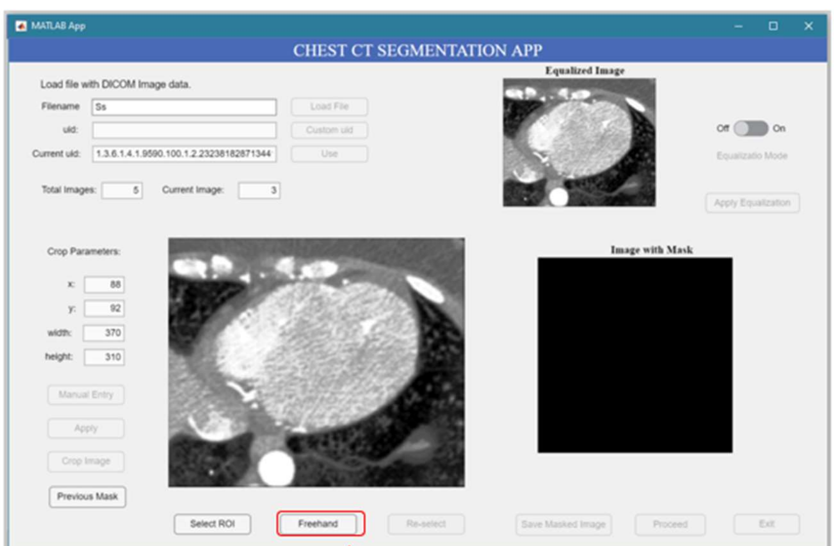
Click 'Exit' to close the program.

Added functionality as of 2/10/21.

G) Using Freehand

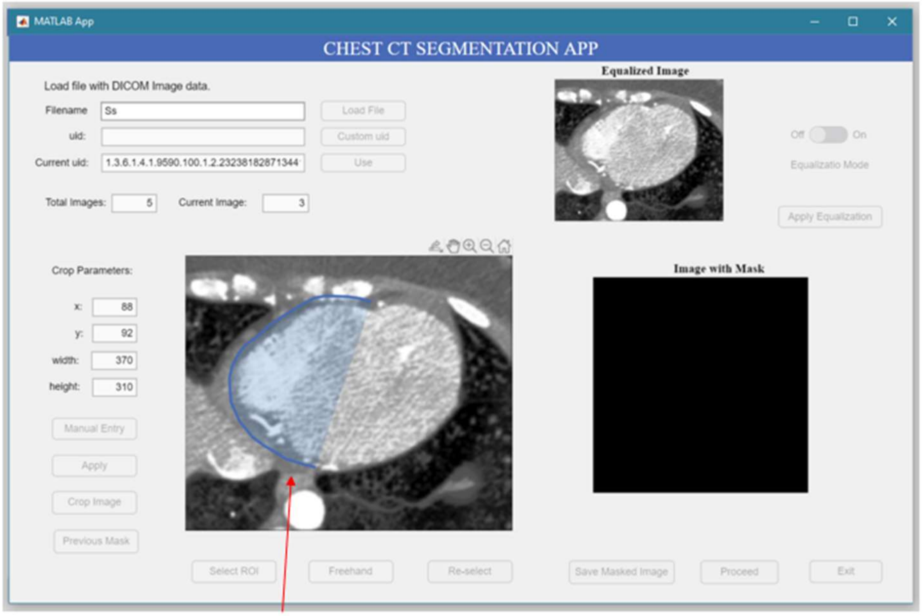
The freehand option allows the user to draw any ROI on the image freely.

1. To begin drawing, crop the image and click on 'Freehand'.

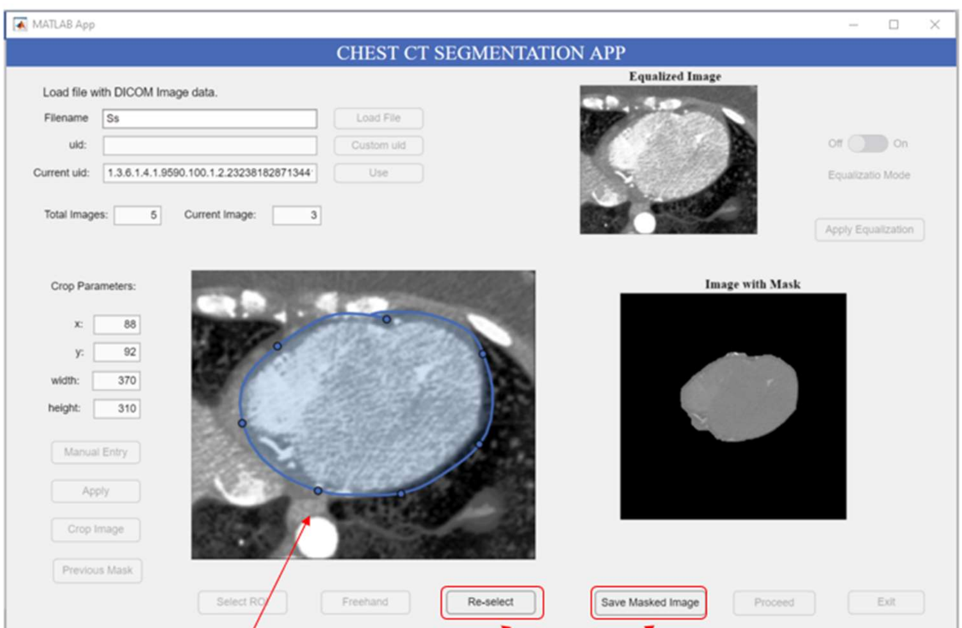


1. Click to start drawing.

2. Hover your mouse pointer on top of the image until a '+' cursor appears and start drawing.



2. Finish drawing around region of Interest with your mouse.



3. Release mouse to see the result.

4. Click 'Save Masked Image' to save the result or 'Re-select' to reset drawing options.

REFERENCES

[1] Aimar A, Palermo A, Innocenti B. The Role of 3D Printing in Medical Applications: A State of the Art. *J Healthc Eng*. 2019; 2019:5340616. Published 2019 Mar 21. doi:10.1155/2019/5340616

[2] Bailer, R., & Martin, R., 2nd (2019). The effectiveness of using 3D reconstruction software for surgery to augment surgical education. *American journal of surgery*, *218*(5), 1016–1021. https://doi.org/10.1016/j.amjsurg.2019.07.045

[3] Basit H, Brito D, Sharma S. Hypertrophic Cardiomyopathy. [Updated 2021 Jan 24]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2021 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK430788/

[4] Byrne, N., Velasco Forte, M., Tandon, A., Valverde, I., & Hussain, T. (2016). A systematic review of image segmentation methodology, used in the additive manufacture of patient-specific 3D printed models of the cardiovascular system. *JRSM cardiovascular disease*, *5*, 2048004016645467. https://doi.org/10.1177/2048004016645467

[5] Larobina, M., & Murino, L. (2014). Medical image file formats. *Journal of digital imaging*, *27*(2), 200–206. https://doi.org/10.1007/s10278-013-9657-9

[6] Maher, M. M., Kalra, M. K., Sahani, D. V., Perumpillichira, J. J., Rizzo, S., Saini, S., & Mueller, P. R. (2004). Techniques, clinical applications and limitations of 3D reconstruction in CT of the abdomen. *Korean journal of radiology*, *5*(1), 55–67. https://doi.org/10.3348/kjr.2004.5.1.55

[7] Pagidipati, N. J., & Gaziano, T. A. (2013). Estimating deaths from cardiovascular disease: a review of global methodologies of mortality measurement. *Circulation*, *127*(6), 749–756. https://doi.org/10.1161/CIRCULATIONAHA.112.128413

[8] Sun Z. (2018). 3D printing in medicine: current applications and future directions. *Quantitative imaging in medicine and surgery*, *8*(11), 1069–1077. https://doi.org/10.21037/qims.2018.12.06

[9] Virzì, A., Muller, C. O., Marret, J. B., Mille, E., Berteloot, L., Grévent, D., Boddaert, N., Gori, P., Sarnacki, S., & Bloch, I. (2020). Comprehensive Review of 3D Segmentation Software Tools for MRI Usable for Pelvic Surgery Planning. *Journal of digital imaging*, *33*(1), 99–110.

[10] Willemink, M. J., Koszek, W. A., Hardell, C., Wu, J., Fleischmann, D., Harvey, H., Folio, L. R., Summers, R. M., Rubin, D. L., & Lungren, M. P. (2020). Preparing Medical Imaging Data for Machine Learning. *Radiology*, *295*(1), 4–15. https://doi.org/10.1148/radiol.2020192224

BIOGRAPHICAL INFORMATION

Shiska Raut is a biomedical engineering and computer science student at the University of Texas at Arlington. She joined UTA's Honors College in 2018 and has also been a member of the Phi Kappa Phi Honors Society since 2020.

Shiska's interest in early diagnosis of cancer sparked her interest in biomedical engineering. As an avid programmer she loves problem-solving by integrating knowledge and ideas from both fields. Her research interests lean towards the application of Artificial Intelligence and Deep Learning algorithms in the area of medical imaging as well as tissue engineering for early detection and diagnosis of diseases.

In 2019, Shiska worked on a tissue engineering project that involved designing a Total Shoulder Replacement Implant. Shoulder replacement implants are used to replace the shoulder joints in patients suffering from end-state shoulder arthritis. The project involves identifying a potential problem with a currently available implant on the market and designing an implant that could solve a problem.

As an international student, Shiska was also involved with the Biomedical Engineering Society and Nepalese Student Association at UTA. After receiving her undergraduate degree, Shiska plans on pursuing a master's degree in computer science at UTA focusing on the application of deep learning and imaging informatics in medicine.