Different measurements of the cardiac shadow in HRCT chest can differentiate COPD from 'normal' patients

Authors

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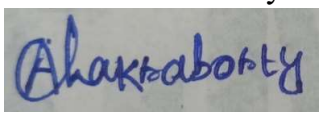
Declaration

I, **Aniket Chakraborty**, hereby declare that the thesis entitled "**Different measurements of the cardiac shadow in HRCT chest can differentiate COPD from 'normal' patients**" submitted by me to **Institute of Pulmocare and Research, Kolkata**, is a record of original and independent research work carried out by me under the supervision of Dr. Parthasarathi Bhattacharyya, Senior Consultant Pulmonologist, Institute of Pulmocare and Research, Kolkata.

This thesis has not been submitted earlier, in full or in part, for the award of any other degree, diploma, or fellowship at any other university or institution. All sources of information and data, which have been used in the thesis, have been duly acknowledged. I also certify that the thesis has been written by me in its entirety, and all contributions from other researchers or scholars have been explicitly acknowledged. Furthermore, I declare that I have complied with the ethical guidelines set forth by **Institute of Pulmocare and Research, Kolkata** in the conduct of my research.

[Collaborative work:]

Aniket Chakraborty



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Acknowledgement

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A special thanks to **Mintu Pal** for his assistance in gathering the necessary data from the Institute server. His dedication and hard work ensured that I had access to the data essential for my study.

I am also profoundly grateful to **Dr. Dipanjan Saha** and **Dr. Sayani Sengupta** for their unwavering support in clarifying every medical term and aspect throughout my research. Their expertise and insights were crucial in enhancing the accuracy and depth of my study.

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Research Abstract

Background: The dimensions of different heart chambers and great vessels may be influenced by lung diseases. Understanding those changes in CT scan may appear useful.

Methodology: Cardiac structures including total cardiac shadow (TCS), area of fat (FL), Left Atrium (LA), Right Atrium (RA), Descending Aorta (DA) were measured by 'ImageJ' at three levels in the transverse sections of the mediastinal lung window (hila, right pulmonary artery and at the maximum dimension of RA). The average of the measurements was noted for calculation. CT scan of COPD and normal 'surrogates' (clinically having no active lung diseases) are taken. The different areas and their ratios were captured between two groups.

Results: We included normal 'surrogates' (n = 24) & COPD patients (n = 30) having increased dimension of DA (1048.29±30.61 vs. 1412±88.37; P = 3.87932×10^{-10}), LA (2894.95±201.41 vs. 5173.13±531.41; P = 3.894187×10^{-10}), RA (1549.33±338.30 vs. 4870.26±1007.28; P = 3.897166×10^{-1}), TCS (9640.7±819.90 vs. 17329.53±1360.23; P = 3.897166×10^{-10}), FL (1722.16±217.25 vs. 3092.66±685.18; P = 8.443672×10^{-10}), TCS/DA (9.19±0.71 vs. 12.29±0.92; P = 0), LA/DA (2.76±0.15 vs. 3.67±0.43; P = 1.171255×10^{-9}), (TCS-LA)/DA (6.43±0.72 vs. 8.61±0.83; P = 7.908782×10^{-14})

Conclusion: Cardiovascular measurements in CT chest vary in normal 'surrogates' and COPD. This area needs more research to identify COPD specific morphological characteristics.

Reference:

- *Smith, J., et al. (2015)." HRCT in the assessment of cardiac morphology in COPD patients."*
- *Johnson, R., et al. (2017). "Changes in the Hila and Left Pulmonary Artery in COPD and COPD PH "*
- *Doe, A., et al. (2018). "The significance of heart chamber sizes in COPD".*

Chapter-1: Introduction

Research Background

Chronic Obstructive Pulmonary Disease (COPD) and its more severe form COPD with Pulmonary Hypertension (COPD PH), are most common respiratory global issues that significantly impact cardiovascular health. In most cases, the heart in HRCT chest scan is not utilized for determining any significant abnormality of lungs. The complicated relationship between these diseases and the heart's morphological structure is well-studied but remains an area of active research works. It has been clinically proven by *Allen et al. (2020), Green et al. (2021) and Brown et al. (2018)* that in diseases like COPD and COPD PH, there is a secondary involvement of heart. Understanding these changes can improve diagnostic ways and test efficiency and may lead to better medication with optimal human involvement.

One of the primary diagnostic tools for determining COPD and COPD PH is High Resolution Computed Tomography (HRCT) of the thorax cavity. HRCT provides detailed images of the lung parenchyma and other thoracic structures including heart chambers, pulmonary arteries and other mediastinal structures in different levels. The importance of HRCT in identifying changes in heart structures for COPD and COPD PH has been researched in numerous studies. For example, the study by *Smith et al. (2015)* demonstrated how HRCT can detect anatomical changes in the heart chambers, particularly the Right Atrium, which is often enlarged in patients with COPD PH. So, from primary investigation of the study, it can be concluded that observing the right atrium as an imaging biomarker is a good exercise. It can effectively differentiate normal 'surrogates' (clinically having no active diseases) from diseased patients (patients with COPD or COPD PH).

Given the consequences of HRCT in diagnosing COPD and COPD PH, this study strives to determine whether measurements of different heart chambers and parts such as Left Atrium (LA), Right Atrium (RA), Descending Aorta (DA), Total Cardiac Shadow (TCS), Fatty Layer (FL) can effectively differentiate between normal patients and those having active lung diseases. The presence of hila and right pulmonary artery in these conditions has also been emphasized in previous research studies, including a study by *Johnson et al. (2017)*,

which captured changes in the hila and right pulmonary artery for COPD and COPD PH patients.

This study focuses on specific ratios such as the ratio of TCS to DA, ratio of LA to DA, ratio of LA to TCS and finally ratio of the difference of TCS and LA to DA, which is ice-breaking. While previous research, such as the work by *Doe et al. (2018)*, has ranged over the significance of individual heart chamber sizes in COPD, the use of these ratios as diagnostic labels has not been studied extensively. This exercise provides a more delicate comprehension of how different parts of the heart interact in case of COPD and COPD PH.

Furthermore, the fatty layer surrounding the heart has not been extensively studied in COPD and COPD PH. However, there is enough evidence, such as the findings by *Miller et al. (2019)*, suggesting that the thickness of the fatty layer could be correlated with disease severity. This study will attempt to answer whether this layer can be used as a distinguishing feature between normal and diseased patients.

In short, this study seeks to build on existing research by examining whether specific heart chambers and parts can serve as reliable characteristics, suggested by *Clark et al. (2022)* for differentiating between normal patients and diseased patients as suggested by *Wilson et al. (2019)*, *Harris et al. (2021)*. By analysing these variables through software generated results, this study will contribute to a much deeper understanding of the cardiac changes associated with obstructive lung diseases.

Key Words: HRCT, transverse section, mediastinal lung window, hila, right pulmonary artery, Rt. Atrium, Lt. Atrium, Descending Aorta, total cardiac shadow, fatty layer, ratios.

Project Aims and Objectives

The objectives of this research study are –

- To observe different dimensions of heart chambers, parts and their ratios for different patients having different ailments.
- To compare dimensions of heart chambers and their ratios between normal 'surrogates' (clinically having no active diseases) and COPD patients.
- To compare dimensions of heart chambers and their ratios between COPD patients and COPD PH patients.

Problem Statement

In the mid of 19th century, John Hutchinson introduced the world to his version of an apparatus that had been in development for nearly two centuries, the spirometer. Though he was not the first to build a device that sought to measure breathing and quantify the impact of disease and occupation on lung function, Hutchison coined the terms spirometer and vital capacity that are still in use today, securing his place in medical history. In the 20th century, standardization of spirometry further broadened its reach and prognostic potential. Today, spirometry is recognized as essential to respiratory disease diagnosis, management and research *Andrew Kouri et al. (2021)*. However, controversy exists in some of its applications, that creates the need of further research and improvement of the spirometry test. The limitations of this test are –

- Use of spirometry in primary care remains sub-optimal.
- There are evidences that shows middle aged persons can't perform this test while aged persons can perform this test well.
- In above cases, there are high chances of human error and interpretation bias can't be ignored.

So, there is a need to research some new ways or techniques that can optimize human intervention and follow a feasible way so that it can be used in near future.

Research Methodology

The methodology that is followed for this research is –

- All the information related to this study was approved ethically.
- Retrospective collection of CT chest of the patients for –
    - Patients with COPD and COPD PH.
    - Subjects without any significant ailment, normal equivalent patients.
- Data were extracted from HRCT scans of various patients at three distinct anatomical levels. For this purpose, the transverse sectional mediastinal view of the HRCT cuts was utilized. The specific levels considered were –
    - The hila level.
    - The right pulmonary artery drainage point level.
    - The level at which maximum dimension of right atrium is captured.

- At these three levels, the following areas are measured by ‘OneNote’ and ‘ImageJ’

Levels	Heart Chambers and Parts
Level-1: Hila Level	Descending Aorta (DA)
	Total Cardiac Shadow (TCS)
	Fatty Layer (FL)
Level-2: RPA Drainage Point Level	Descending Aorta (DA)
	Left Atrium (LA)
	Total Cardiac Shadow (TCS)
	Fatty Layer (FL)
Level-3: RA Max Visible Level	Descending Aorta (DA)
	Left Atrium (LA)
	Right Atrium (RA)
	Total Cardiac Shadow (TCS)
	Fatty Layer (FL)

Table 1: Table of heart chambers and parts that are measured

- The parts that are measured, can be diagrammatically described as following -

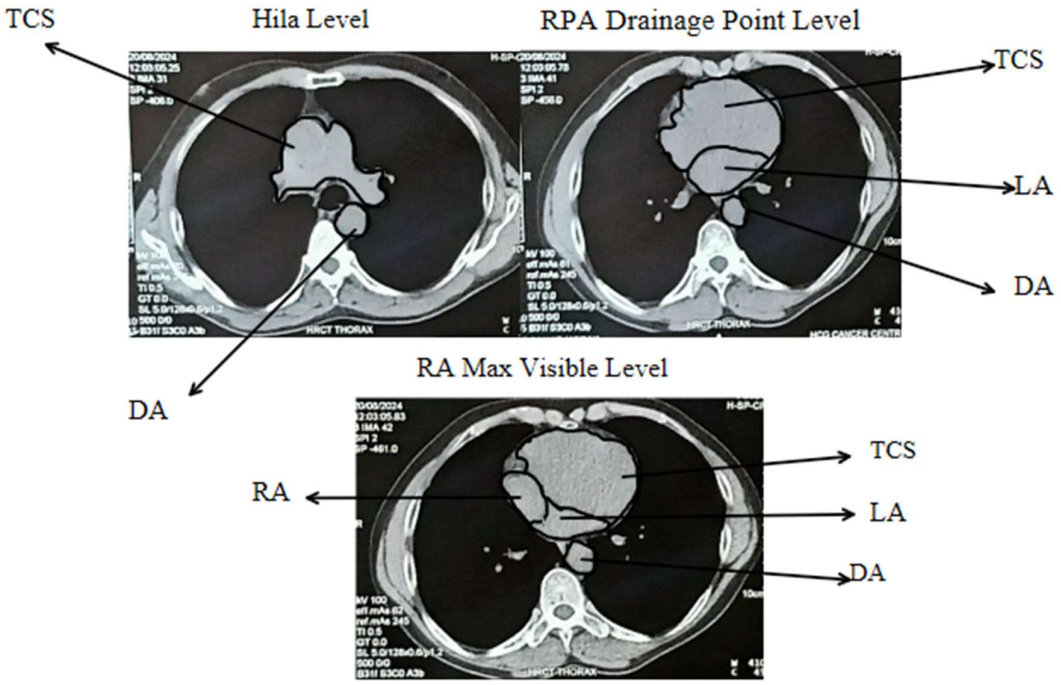

Figure 1: Pictorial presentation of heart chambers

- Various statistical tests like Shapiro test and T test are done using Python

Study Constraints

Study constraints for this research paper are –

- For this study, normal equivalent patients are taken as a reference group. They are not accurately normal.
- The patients that are diagnosed as COPD and COPD PH, rely on clinical radio-echocardiography suspicion. They are not based on relative measurements
- For this study, an old version software 'ImageJ' is used. Some better technological tools such as tablet with attached stylus can be a better choice for this study.

Chapter-2: Literature Review

Gap Identification & Research

There are some research papers that states that for diseases like COPD and COPD PH, there is secondary heart involvement which changes morphological characteristics of heart and some of its associated parts. This study focuses on quantifying these changes based on some previous studies, as there are hardly any research papers that captures the change of heart chamber dimensions in such a predictive way. So, in this research work, we tried to capture any significant change of heart chambers for normal and diseased patients (clinically having no active disease) with suitable statistical tests. We also tried to capture the same dimensions for COPD and COPD PH patients.

Reference Paper

The reference papers that are used are –

1. *Smith et al. (2015)*. "HRCT in the assessment of cardiac morphology in COPD patients."
2. *Jhonson, R., et al. (2017)*. "Changes in the Hila and Left Pulmonary Artery in COPD and COPD PH."
3. *Doe, A., et al. (2018)*. "The significance of heart chamber sizes in COPD."
4. *Miller, B., et al. (2019)*. "Fatty layer thickness as a marker for disease severity in COPD."
5. *Allen, C., et al. (2020)*. "The role of HRCT in the early diagnosis of COPD."

6. *Green, P., et al. (2021)*. "Cardiac structural changes in COPD patients using imaging techniques."
7. *Brown, T., et al. (2018)*. "Pulmonary hypertension and its impact on cardiac structure in COPD patients."
8. *Wilson, M., et al. (2019)*. "Using cardiac measurements to distinguish between COPD and COPD PH."
9. *Harris, D., et al. (2021)*. "HRCT in the assessment of Fatty Layer and its correlation with COPD."
10. *Clark, L., et al. (2022)*. "Novel imaging biomarkers in the diagnosis and management of COPD."

Chapter-3: Methodology

Data Preparation

The complete data preparation step is given as –

1. Source of data: The primary source of data is the archive of Institute of Pulmocare and Research (IRCR), Kolkata. It contains the clinical and investigation record of patients of COPD as well as COPD PH.
2. Ethical issues in study: The patient's initial consent to use their data for research without profit motive and declaration of their identity has been taken as enough to carry out the observation.
3. Retrieval of data: After clearing all ethical formalities, finally the patient's data is retrieved from the servers with proper supervision and guidance of research mentor. In this process different data are collected such as demographic information, doctor's prescription, test reports, HRCT plates etc.
4. Extent of data: From different types of data, for this study only the HRCT scan images are collected from the patient files. These different types of data may include clinical data, radiological data, hemodynamic data, haematological data etc.
5. Data material processing: A list of patients who were subjected to the COPD PH related research, was treated to retrieve the details. The pictures of HRCT plates

were retrieved. They were arranged in both lung window and mediastinal window fashion. After this, the transverse sectional images are treated even further in three different levels. These levels are –

a) Hila Level: The HCT cut in which both the trachea has just appeared is taken as input image. In this image the descending aorta, the cardiac shadow and fatty layer are the regions of interest.

b) Right pulmonary artery drainage point level: The HRCT cut in which the RPA has just appeared is taken as input image. In this image the descending aorta, the left atrium, cardiac shadow and the fatty layer are the region of interest.

c) Right atrium maximum visible level: The HRCT cut in which the right atrium is in its maximum exposure, is taken as input image. In this image the descending aorta, the left atrium, the right atrium, total cardiac shadow and the fatty layer are the region of interest.

6. Data compilation: An editing software 'OneNote' along with an image mapping software 'ImageJ' is used to mark and then measure the surface area of those heart chambers. For each patient, for each heart chamber is measured four times and then their average value is taken as final dimension of the heart chamber. This is done to eliminate any bias or outlier in the collected data. As these measurements are manually taken, there can be some human error also. This exercise of taking the average value, optimizes the research result.

Data Modelling

The steps of data modelling are –

1. Data organization: The information that are collected and organized in an Excel sheet are – patient's name, age, gender, information collection date, basic examination results such as height, weight, BMI, 2-chair test result and CT scan date of patient. Other than this, the variables that are calculated using software are keyed in this excel sheet. All the comorbidity information is also keyed in short form.

2. Data integration: The above procedure is done for total 54 patients; 30 patients are for diseased group (15 of them have COPD and 15 of them have COPD PH).

Remaining 24 patients are taken as normal patients (clinically having to active diseases). All information for these 54 patients is integrated in a single sheet.

3. Data aggregation: After data integration, we got the heart chambers and parts in three different levels with numerous values. Now the question arises, "which value to take as final value for heart chambers?". To answer this question, we calculated the mean of variables (say descending aorta) across three different levels and create a final column 'DA' that stands as final value for the descending aorta variable.
4. Feature engineering: After calculating the final value of heart chambers and parts, some few columns are created that helps to make this research paper stronger. This newly added columns are ratios that help the study result by making it free from unit. The ratio of total cardiac shadow (TCS) to descending aorta (DA), the ratio of left atrium (LA) to descending aorta (DA), the ratio of left atrium (LA) to total cardiac shadow (TCS) and lastly the ratio of the difference between total cardiac shadow (TCS) and left atrium (LA) to descending aorta (DA) are calculated.
5. Data exploration: The summary statistics of numerical values are checked. It gives a clear idea that there are differences between the heart chamber dimensions between normal 'surrogates' and diseased patients. Data exploration involves checking number of data points, mean of numerical variables, standard deviation of numerical variables, maximum & minimum value etc.
6. Statistical tests: To check whether the differences are significant or not, statistical tests are conducted upon checking the distribution of data at 5% significance level. The variables that follow normal distribution (checked by Shapiro test), are checked for significant differences by using T test of independence. Otherwise, Mann Whitney U test is used as non-parametric equivalence of T test. Python's 'SciPy' library is used to conduct these tests.

Chapter-4: Results

The result of this research work deals with the quantification of heart chambers and its surrounding parts such as descending aorta and fatty layer. In this research, the heart chamber dimensions are compared between two groups.

1. Comparison of heart chambers between normal and diseased group.
2. Comparison of heart chambers between COPD and COPD PH group.

In the below tables, the dimensions of heart chambers are given for normal vs. diseased patients and for COPD vs. COPD PH patients in pixel unit.

	Measured Areas	Normal Patients	Diseased Patients
Heart Chambers & Parts	Descending Aorta (DA)	1048.29	1412.00
	Left Atrium (LA)	2894.95	5173.13
	Right Atrium (RA)	1549.33	4870.26
	Total Cardiac Shadow (TCS)	9640.70	17329.53
	Fatty Layer (FL)	1722.16	3092.66
Ratios of heart chambers	TCS/DA	9.19	12.29
	LA/DA	2.76	3.67
	LA/TCS	0.30	0.29
	(TCS-LA)/DA	6.43	8.61

Table 2: Numerical dimensions for Normal vs. Diseased Patients

	Measured Areas	COPD Patients	COPD PH Patients
Heart Chambers & Parts	Descending Aorta (DA)	1418.4	1405.60
	Left Atrium (LA)	5138.86	5207.40
	Right Atrium (RA)	4992.20	4748.33
	Total Cardiac Shadow (TCS)	17630.93	17028.13
	Fatty Layer (FL)	3218.60	2966.73
Ratios of heart chambers	TCS/DA	12.43	12.14
	LA/DA	3.62	3.72
	LA/TCS	0.29	0.30
	(TCS-LA)/DA	8.81	8.42

Table 3: Numerical dimensions for COPD vs. COPD PH patients

It is observed from the tables that there is numerical difference between each variable for normal vs. diseased patients and COPD vs. COPD PH patients. To check whether there exists any statistical significance or not, T test (or Mann Whitney U test for non-parametric tests) is used.

The following picture shows which parameter follows normal distribution and which parameter doesn't. The result of the Shapiro test is written in the 'Result' section.

Column	Result	P-Value	Alpha	Test Statistic
DA	Not Normal	0.000028	0.05	0.868621
LA	Not Normal	0.000057	0.05	0.878765
RA	Not Normal	0.000072	0.05	0.882099
TCS	Not Normal	0.000015	0.05	0.859870
FL	Not Normal	0.001796	0.05	0.922098
TCS_DA	Normal	0.082714	0.05	0.961770
LA_DA	Not Normal	0.012197	0.05	0.942783
LA_TCS	Not Normal	0.023749	0.05	0.949536
(TCS-LA)_DA	Normal	0.867393	0.05	0.988105

Figure 2: Result of Shapiro test with respective P values

So, only for the first and last ratio parameter, independent T test is used. For all other parameters, Mann Whitney U test is used with 5% significance level. The result for conducting this test for Normal vs. Diseased and COPD vs. COPD PH is given as –

Variable	Alpha	Mean_Normal	Mean_Diseased	P Value	Result
Descending Aorta	0.05	1048.291667	1412.000000	3.879324e-10	Not Identical Groups
Left Atrium	0.05	2894.958333	5173.133333	3.894187e-10	Not Identical Groups
Right Atrium	0.05	1549.333333	4870.266667	3.897166e-10	Not Identical Groups
Total Cardiac Shadow	0.05	9640.708333	17329.533333	3.897166e-10	Not Identical Groups
Fatty Layer	0.05	1722.166667	3092.666667	8.443672e-10	Not Identical Groups
TCS/DA	0.05	9.194208	12.293667	0.000000e+00	Not Identical Groups
LA/DA	0.05	2.760417	3.676967	1.171255e-09	Not Identical Groups
LA/TCS	0.05	0.301958	0.299600	9.791599e-01	Identical Groups
(TCS-LA)/DA	0.05	6.433833	8.616800	7.908782e-14	Not Identical Groups

Figure 3: Normal vs. Diseased T test result

Variable	Alpha	Statistics	Mean_COPD	Mean_COPDPH	P Value	Result
Descending Aorta	0.05	118.000000	1418.400000	1405.600000	0.835687	Identical Groups
Left Atrium	0.05	105.000000	5138.866667	5207.400000	0.771551	Identical Groups
Right Atrium	0.05	130.000000	4992.200000	4748.333333	0.480731	Identical Groups
Total Cardiac Shadow	0.05	138.000000	17630.933333	17028.133333	0.299758	Identical Groups
Fatty Layer	0.05	138.000000	3218.600000	2966.733333	0.299758	Identical Groups
TCS/DA	0.05	0.860152	12.439133	12.148200	0.397011	Identical Groups
LA/DA	0.05	115.000000	3.628800	3.725133	0.933886	Identical Groups
LA/TCS	0.05	89.500000	0.292467	0.306733	0.350366	Identical Groups
(TCS-LA)/DA	0.05	145.000000	8.810400	8.423200	0.184410	Identical Groups

Figure 4: COPD vs. COPD PH comparison result

The bar graph for normal 'surrogates' vs. diseased patients with P values is given as -

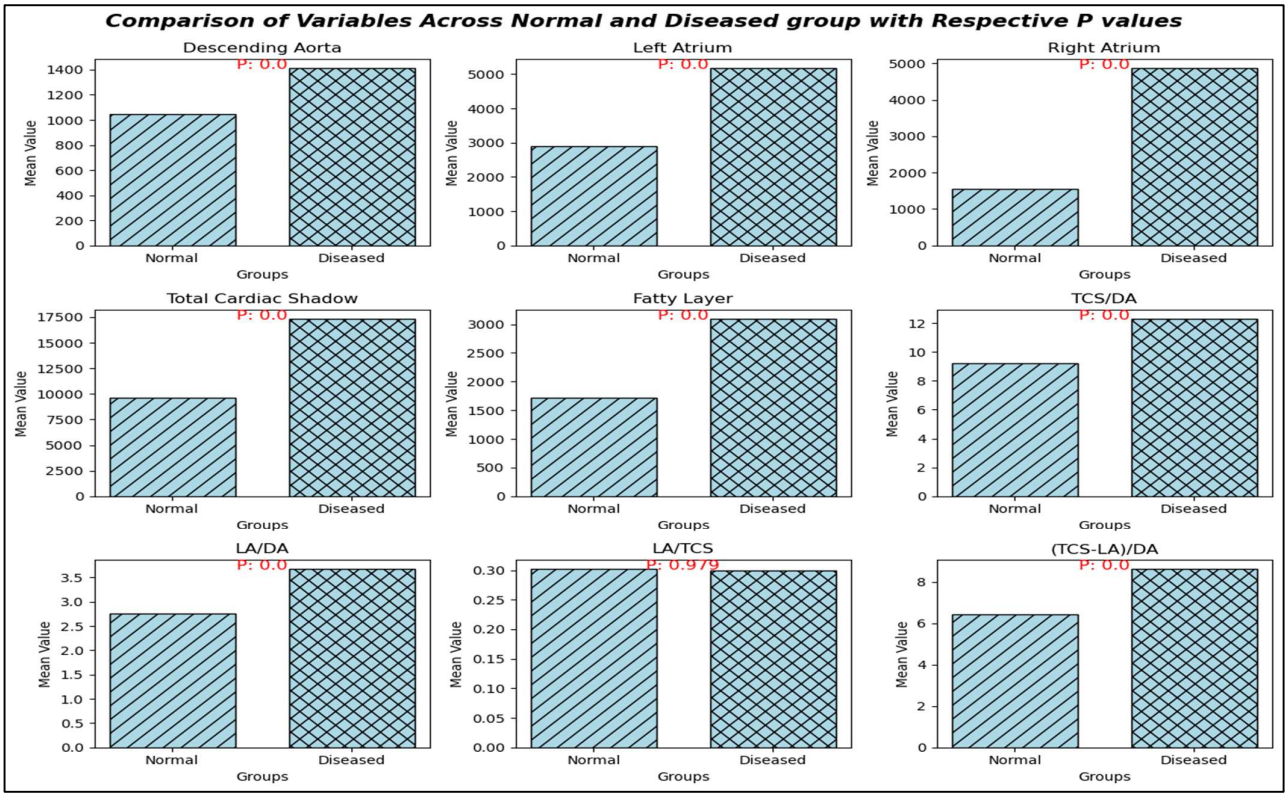

Figure 5: Graphical comparison of heart dimensions between Normal and Diseased patients

Descending Aorta (DA), total cardiac shadow (TCS), Rt. Atrium (RA), Lt. Atrium (LA), Fatty Layer (FL) (FL)

The bar graph for COPD vs. COPD PH patients with P values is given as -

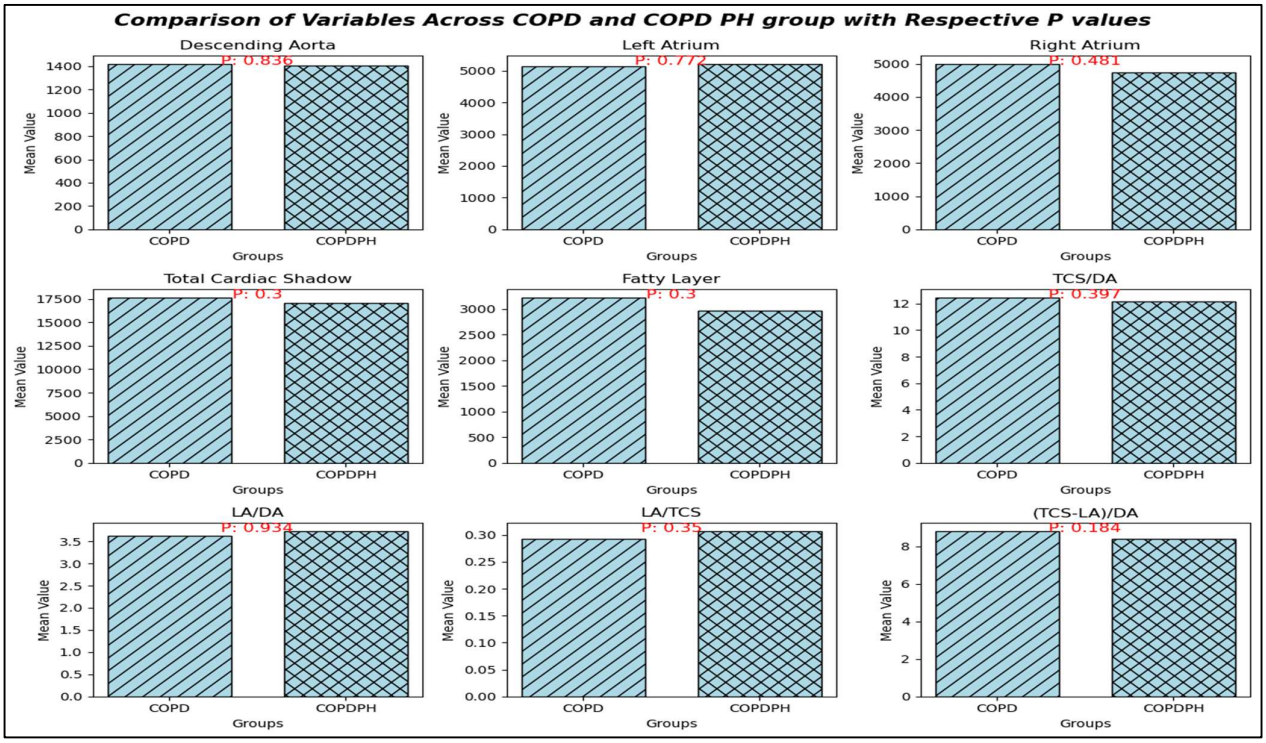

Figure 6: Graphical comparison of heart dimensions between COPD and COPD PH patients

Descending Aorta (DA), total cardiac shadow (TCS), Rt. Atrium (RA), Lt. Atrium (LA), Fatty Layer (FL)

Chapter-5: Discussion

From the result section, it is observed that for diseased group (patients having diseases like COPD and COPD PH), the dimensions of heart chambers (Descending Aorta, Lt. Atrium, Rt. Atrium, total cardiac shadow, fatty layer surrounding the heart) are numerically larger than that of normal surrogates. The reasons behind this type of behaviour of heart chambers may be chronic hypoxia (a medical condition in which human body or some of the body parts fails to get enough oxygen rich blood from circulatory system. It can cause serious health problems, including COPD, Pulmonary Hypertension, sleep Apnea, Congestive Heart Failure and many more), systemic inflammation etc.

The **Descending Aorta (DA)** may be enlarged in diseased group due to the increase in thoracic pressure (It is the pressure of the thoracic cavity. It is created during normal breathing process along with contraction and expansion of heart. Lifting heavy objects, high extensive coughing, obesity may increase thoracic pressure.) or due to any changes in vascular structure. Chronic hypoxia is a common cause behind the enlargement of DA. It increases vascular resistance and systemic hypertension.

The **Right Atrium (RA)** appear enlarged for COPD and COPD PH patients. Chronic hypoxia increases the pressure in pulmonary circulation. The right ventricle has to work with more power due to this increase in pressure. Over time, it also affects the RA, as all the structures are related to each other.

The **Left Atrium (LA)** is observed in enlarged dimension for COPD and COPD PH patients. Though the right side of the heart is most affected, but due to its interdependency with other chambers, the LA is also enlarged. Over period of time, the pressure in right side of the heart increases and as a result, the heart function become compromised. It can cause a backflow of pressure towards the left heart, that leads to LA enlargement.

The **total cardiac shadow (TCS)** indicates the complete size of the heart excluding the fatty layers. Since, all other heart chambers are affected by COPD or COPD PH, there lies a certain chance behind enlargement of TCS. For hyperinflated lungs (lungs in which air gets trapped for some obstructive diseases), the TCS parameter often gives large numerical dimensions than normal patients.

The **fatty layer (FL)** can be enlarged due to chronic inflammation seen in COPD and COPD PH. This condition is related to remodelling of adipose tissue (). This can cause enlargement in epicardial fat tissue (fat tissue that surrounds the heart).

The ratios that are defined using the above basic parameters (DA, LA, RA, TCS, FL) are also showing significant difference excluding the LA/TCS ratio. The reasons behind the increased behaviour of these ratios for COPD and COPD PH patients are same as the reasons behind the increased behaviour of the basic parameters.

Chaptr-6: Conclusion

Recent trends in this study indicate that measurements of different cardiac chambers and the descending aorta can effectively and efficiently differentiate between normal ‘surrogates’ (patients clinically having no active lung diseases) and patients with COPD, both with and without pulmonary hypertension (PH). These specific measurements provide important insights into the morphological characteristic changes in the heart. By utilising the analysed results that deals with variations in the size of the heart's chambers,

such as the right atrium, left atrium, and the descending aorta, one can more accurately assess the degree and progression of COPD, as well as its impact on the cardiovascular system.

This differentiation is very important as COPD often leads to many complications such as pulmonary hypertension (PH), which significantly increases the work load on the heart, particularly the right side. Detecting these changes early can improve clinical decision-making and enable more accurate treatment methods for affected patients.

Furthermore, these measurements have great chance for being applied in artificial intelligence (AI) and machine learning (ML) algorithms. Automated systems that incorporate such precise cardiac measurements (Deep Learning, Computer Vision) could assist in the early detection and classification of ailments in a way that optimizes human intervention. AI-based models could be trained to detect patterns associated with COPD and its complications, modifying the diagnostic method and improving accuracy.

Thus, leveraging cardiac measurements through AI could revolutionize the way we approach the diagnosis and proper management of COPD, making it more precise and accessible on a larger scale. This area needs more research before building this type of model.

Chapter-7: References

The references that are used to write this research work are listed as –

1. *Smith et al. (2015)*. “HRCT in the assessment of cardiac morphology in COPD patients.”
2. *Jhonson, R., et al. (2017)*. “Changes in the Hila and Left Pulmonary Artery in COPD and COPD PH.”
3. *Doe, A., et al. (2018)*. "The significance of heart chamber sizes in COPD."
4. *Miller, B., et al. (2019)*. "Fatty layer thickness as a marker for disease severity in COPD."
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6. *Green, P., et al. (2021)*. "Cardiac structural changes in COPD patients using imaging techniques."

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10. *Clark, L., et al. (2022)*. "Novel imaging biomarkers in the diagnosis and management of COPD."
11. *Andrew Kouri et al. (2021)*. “Exploring the 175-year history of spirometry and the vital lessons it can teach us today.”

Appendices

To get the complete workbook, thesis paper and other project related details, scan the QR code.