Visualization and Shape Analysis of Left Ventricle Using PCA and 3D Modeling

Akash Gupta
B.Tech Biomedical Engineering, NIT Raipur
Intern, IIT BHU (May–July 2025)

Abstract

This project focuses on analyzing and visualizing the 3D shape of the left ventricle (LV) of the human heart using **Principal Component Analysis (PCA)**. Traditional cardiac diagnostics often rely on mass and volume measurements, but these overlook critical shape-related changes that are early indicators of cardiovascular disease. In this project, MRI data from the **Multi-Ethnic Study of Atherosclerosis (MESA)** was used to generate 3D statistical models using the **Cardiac Atlas Project (CAP)** and MATLAB's PCATool. End-diastole and end-systole phases of the cardiac cycle were modeled and exported as 3D STL files, ready for simulation or 3D printing. The work contributes toward understanding heart shape variability and serves as a foundation for future machine learning applications in cardiac health.

1. Introduction

1.1 Background and Motivation

In current clinical practices, cardiac function is evaluated primarily through **mass and volume measurements** of the LV. However, many cardiovascular conditions begin with **subtle changes in the heart's shape**, such as increased sphericity or wall thickening. These cannot be effectively captured through traditional metrics.

The goal of this research is to create a **3D statistical model** of the LV using PCA, which can identify and quantify shape variation. This approach can potentially detect early signs of disease and provide a **standard reference** for comparing diseased versus healthy hearts.

1.2 Why 3D LV Modeling?

- Enables **quantitative analysis** of shape across individuals.

- Detects **early morphological changes** due to diseases like diabetes and hypertension.
- Provides a **standardized tool** for comparing patient hearts to healthy references.
- Enhances **3D visualization** for educational, diagnostic, and surgical planning purposes.

2. Materials and Methods

2.1 Data Collection

The study uses data from the **Multi-Ethnic Study of Atherosclerosis (MESA)**, which includes:

- **Participants:** 1,991 asymptomatic individuals
- **Modality:** Cardiovascular Magnetic Resonance (CMR)
- **Imaging specs:**
  - 1.5T MRI scanners
  - 10–12 short-axis slices per case
  - 20–30 frames per slice
  - Temporal resolution: < 50 ms
  - Pixel size: 1.4–2.5 mm

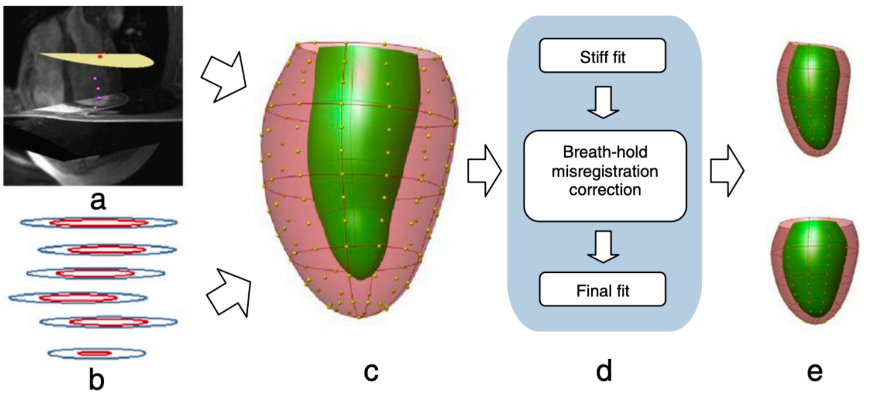


Figure 1 Flow chart of the atlas construction. (a) Fiducial landmarks defined at ED on short and long axis images (3D view from anterior). Red markers denote the mitral valve and purple markers denote the intersections of the right ventricular free wall and the septum. The base plane is drawn as a yellow disc. **(b)** Contours drawn on short axis slices by the core lab. Individual breath-holds for each 2D slice result in mis-alignment between slices. **(c)** 3D finite element model showing epicardial control points (model shape parameters) and element boundaries. **(d)** Breath-hold mis-registration correction by alignment to the model. **(e)** Principal component analysis of atlas shape variation. Upper and lower panels show ±2 standard deviations in the principal component shape.

2.2 Dataset and Tools

Source: [Cardiac Atlas Project GitHub Repository]

Data Files Used:

- `PCA_ED.mat` – PCA model at end-diastole
- `PCA_ES.mat` – PCA model at end-systole
- `SurfaceFaces.mat` – Triangle mesh for surface visualization

Tools: MATLAB Online, PCATool

3. Principle and Implementation

3.1 PCA in Medical Imaging

Principal Component Analysis (PCA) is a dimensionality reduction technique used to:

- Simplify large datasets while preserving significant patterns.
- Identify **dominant modes of shape variation**.
- Extract meaningful features (principal components).
- Enable **faster ML model training** by reducing redundancy.
- Visualize complex 3D cardiac structures.

3.2 MATLAB Implementation Steps

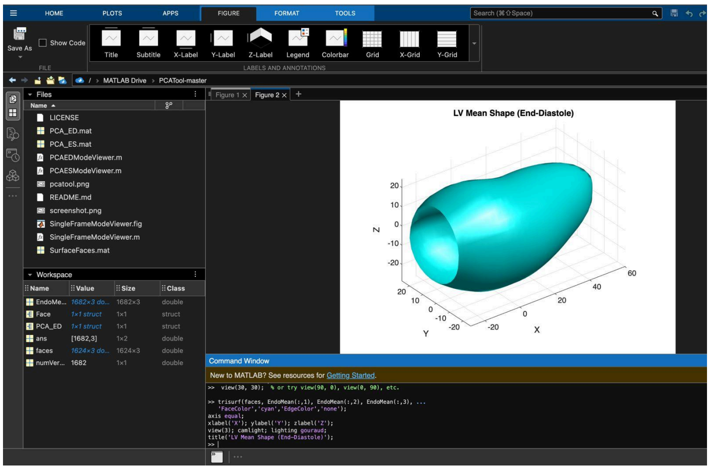
- **Load .mat files** into MATLAB Online.
- **Extract mean shapes** from `PCA_ED.MEAN` and `PCA_ES.MEAN`.
- **Load triangle mesh** from `Face.Endo` in `SurfaceFaces.mat`.
- Use `trisurf()` to **plot and visualize** the 3D surface.
- Export STL files using `stlwrite()` for 3D printing or CAD simulations.

4. Results and Observations

4.1 LV Shape Visualization

The MATLAB-based implementation successfully generated:

- **LV Mean Shape at End-Diastole**
- **LV Mean Shape at End-Systole**



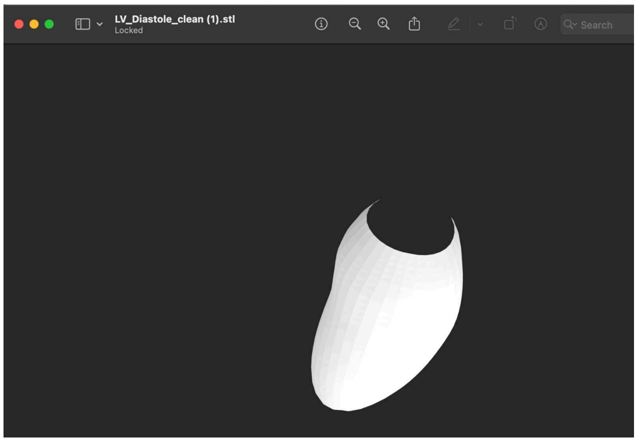
4.2 STL Export

Exported STL files:

- `LV_Diastole_clean.stl`
- `LV_Systole_clean.stl`

Can be used for:

- 3D printing
- CAD simulations
- Medical animations



5. Discussion

The analysis of the shape of the LV revealed that the major modes of variation are related to:

- Size (scale of the LV)
- Sphericity (roundness or elongation)

- Concentricity (wall thickness)

These features are clinically significant as they are often linked to adverse cardiac remodeling caused by hypertension, heart failure, or ischemia. The 3D models allow better understanding and offer early indicators of cardiovascular risk, especially in asymptomatic individuals.

The method also provides a reference framework for future machine learning models in cardiology. By using PCA, we can parameterize heart shapes and compare them across populations with high accuracy.

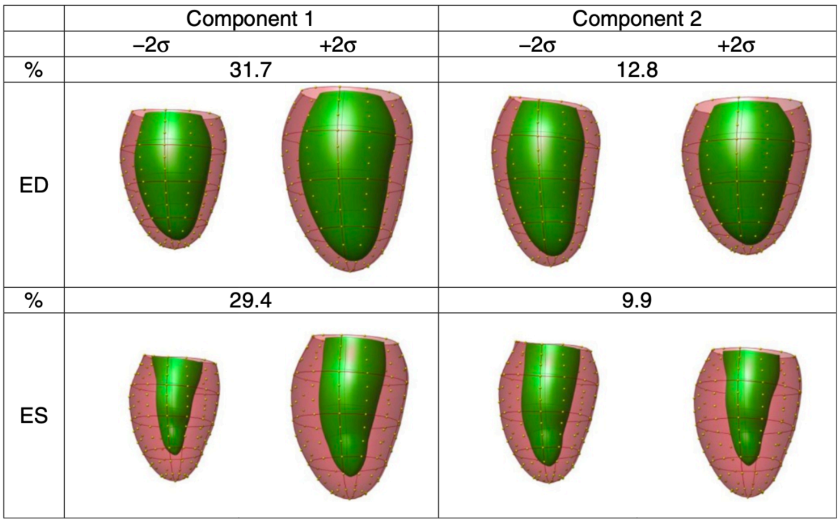


Figure 3 First and second principal shape components of variation in the atlas (N = 1,991) for ED and ES. For each component the left and right shapes represent the mean ± 2 std. dev. in the component distribution. Viewpoint is from the septum, posterior wall on the right.

6. Conclusion

This project demonstrates that 3D PCA-based modeling of the left ventricle is a valuable technique for understanding cardiac morphology. It not only offers improved visualization but also opens new avenues in:

- Early disease detection
- Simulation-based training
- Surgical planning
- Biomechanical research

The STL models generated are accurate and exportable, making them suitable for practical applications in research, education, and clinical simulations.

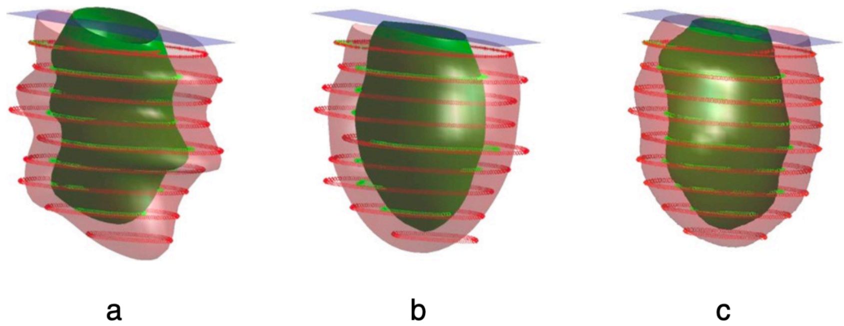


Figure 4 Breath-hold correction. (a) original contours with a superimposed low- stiffness fit; **(b)** highly stiff model which serves as a guide for breath-hold correction; **(c)** final fit with low stiffness and corrected contours. Epicardial contours and surfaces are shown in blue; endocardial contours and surfaces are shown in red.

7. Learnings

- Gained hands-on experience with MATLAB and cardiac datasets.
- Learned implementation of PCA in biomedical imaging.
- Understood the process of 3D shape modeling from medical imaging data.
- Developed skills in STL model generation, ready for real-world CAD or simulation tasks.