Chapter 1 Introduction

1A. Goals and Motivation

In many aspects of modern medicine, medical images provide crucial information for diagnosis and treatment. Doctors and other health professionals rely heavily on their ability to identify and measure objects seen in these images. This process is often painstaking and time consuming. Therefore, the goal of automated identification and measurement of objects in medical images is of critical importance.

Nowhere is this more evident than in the automated analysis of images of the cardiac left ventricle using Real Time Three-Dimensional (RT3D) ultrasound. RT3D ultrasound is a new imaging modality that scans the entire heart in real time, providing an important new means for rapidly diagnosing many types of heart disease. Because of the large number of 3D scans produced every second, however, manual analysis is extremely labor intensive making it a prime candidate for automation.

Automated analysis of medical images, in general, has met with difficulty because noise, variation in anatomical shape, varying imaging characteristics, and incomplete target boundaries make the identification of anatomical structures unreliable. Ultrasound in particular suffers from these problems, with additional difficulties arising from the path dependence of the ultrasound signal and the non-rectilinear coordinate system in which the data are collected. Among ultrasound technologies, RT3D has especially high noise and low resolution, a trade-off made to achieve 3D imaging and high speed. The potential benefit of automating the analysis of this new data set, however, makes the challenge well worth accepting.

A reasonable first goal for automated analysis of RT3D echocardiographic data is the determination of left ventricular volume. Such a measurement does not require, as might be assumed, that a single optimal boundary be delineated for the ventricle but rather that the ventricle be identified as a whole and its volume determined in some manner. To be of practical value, the determination of left ventricular volume must be rapid and robust, with an emphasis on avoiding catastrophic failure.

A shape necessarily depends on the geometric relationships between points on its boundary. Methods of shape detection generally proceed either by means of *deformable models* that search

across potential sets of neighboring boundary points, or *ridge tracking* techniques that search along them. The instability of local image measurements, especially in ultrasound, suggests that examining a more dispersed population of boundary measurements may produce more stable and robust measurements, not of boundaries, but of entire sections of anatomy. Various possible geometric relationships between boundary points in a population could be used to organize them. One that is particularly powerful is the *medial* relationship, which links boundary points equidistant from the center of an object. Pairs of boundary locations related through a common relationship with a medial location have been called *medial primitives*.

This dissertation explores the suggestion that the identification and measurement of objects in 3D images can be automatic, rapid and stable, based on the statistical properties of populations of medial primitives sought throughout the image space. These properties include medial location, scale, orientation, and dimensionality. The property of medial dimensionality differentiates the sphere, cylinder, and the slab, with intermediate dimensionality also possible. The values of these medial properties at just a few locations provide an intuitive and robust model for representing complex shapes. This dissertation will develop a particular example in which the left ventricle during systole is described as a large cylinder with an apical cap at one end and with a slab-like mitral valve at the other (closed during systole). The model includes appropriate interrelations among these components in terms of their scale, orientation, and location.

A method is developed to extract populations of medial primitives called *core atoms*. In core atoms, pre-detected boundary points are associated in non-exclusive pairs that face each other across an object. For each core atom, a central location is calculated midway between the boundary points. Core atoms are grouped by their centers into populations that form clouds at medial locations. The populations of core atoms provide a statistical means of identifying locations with high *medialness* and yield measures of the medial properties listed above. In addition, once regions of high medialness are established, unpaired boundary points can be sought at the ends of cylinders or the edges of slabs, permitting identification of locations with high *endness* at specific anatomical structures such as the apex of the LV.

I aim to show that statistics performed on medial primitives permit the identification of anatomical landmarks. A *medial node model* based on multiple landmarks may then be matched to the data, using the associations between landmarks. Subsequent determination of volume for the underlying structure may then proceed *without explicit delineation of its boundaries*. I shall demonstrate this method on simple geometric test objects and show it capable of automatically identifying and measuring the volume of the left ventricle *in vivo* using RT3D ultrasound. The method provides sufficient robustness, accuracy, and speed to be clinically useful for RT3D echocardiographic analysis.

1B. Claims

Claim #1.

Automated measurement of ventricular volume is possible in RT3D echocardiographic data using a statistical analysis of voxel intensity and location with respect to a medial node model (described in Claim #2).

Claim #2.

Automated identification of anatomical structures is possible in RT3D echocardiographic data using correspondences between a medial node model of the heart and a set of medial measurements extracted empirically from the image data (described in Claim #3).

Claim #3.

The medial properties of scale, orientation, dimensionality, and endness can be extracted from cardiac image data by clustering regularly sampled populations of medial primitives (described in Claim #4).

Claim #4.

A set of candidate boundary points can be collected in an image and medial primitives formed from pairs of these boundary points with appropriate relative distance and orientation. The medial primitives can be sorted by location to provide for statistical analysis of local medial properties.

Claim #5.

Evaluation of these methods on parametric test objects, fluid-filled balloons, and *in vivo* human hearts establishes the ability of the method to match a model to the image data and determine the volume of the underlying anatomical structure.

1C. Guide to Chapters

This dissertation is organized into eight additional chapters, followed by appendices and references. Chapter 2 provides a background for cardiac imaging and image analysis techniques, as well as an overview of the present method of analysis. Chapter 3 defines the medial primitive, called the *core atom*, and develops the statistical analysis of local samples of core atoms. Chapter 4 deals with understanding and compensating for spatial sampling artifacts in local populations of core atoms. Chapter 5 describes medial node models, which incorporate expected medial properties at multiple locations and their geometric relationships, as well as how to match them to medial measurements in the image. Chapter 6 covers issues arising from the coordinate system and physics of RT3D ultrasound. Chapter 7 develops a theoretical approach for determining volume based on the medial aspects of shape and describes a statistical method for assigning to a voxel the probability of being inside the ventricle, based on intensity and location with respect to a medial node model. Chapter 8 reports empirical results for measuring volume of fluid-filled balloons and identifying and measuring the LV *in vivo* with RT3D ultrasound. Chapter 9 concludes the dissertation with a review of the claims, a discussion of the strengths and weakness of the approach, and an indication of directions for future research. The appendices describe particular algorithms and mathematical techniques in greater detail.