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Measurement of Mitral Leaflet and Annular Geometry and Stress After Repair of Posterior Leaflet Prolapse: Virtual Repair Using a Patient-Specific Finite Element Simulation

Liang Ge, PhD,* William G. Morrel, BS,* Alison Ward, MD, Rakesh Mishra, MD, Zhihong Zhang, MS, Julius M. Guccione, PhD, Eugene A. Grossi, MD, and Mark B. Ratcliffe, MD

Departments of Surgery, Bioengineering, and Medicine, and the School of Medicine, University of California, San Francisco, California; Veterans Affairs Medical Center, San Francisco, California; and Department of Cardiothoracic Surgery, New York School of Medicine, New York, New York

Background. **Recurrent mitral regurgitation after mitral valve (MV) repair for degenerative disease occurs at a rate of 2.6% per year and reoperation rate progressively reaches 20% at 19.5 years. We believe that MV repair durability is related to initial postoperative leaflet and annular geometry with subsequent leaflet remodeling due to stress. We tested the hypothesis that MV leaflet and annular stress is increased after MV repair.**

Methods. **Magnetic resonance imaging was performed before and intraoperative three-dimensional (3D) transesophageal echocardiography was performed before and after repair of posterior leaflet prolapse in a single patient. The repair consisted of triangular resection and annuloplasty band placement. Images of the heart were manually co-registered. The left ventricle and MV were contoured, surfaced, and a 3D finite element (FE) model was created. Elements of the posterior leaflet region were removed to model leaflet resection and virtual sutures were used to repair the leaflet defect and attach the annuloplasty ring.**

Results. **The principal findings of the current study are the following: (1) FE simulation of MV repair is able to accurately predict changes in MV geometry including changes in annular dimensions and leaflet coaptation; (2) average posterior leaflet stress is increased; and (3) average anterior leaflet and annular stress are reduced after triangular resection and mitral annuloplasty.**

Conclusions. **We successfully conducted virtual mitral valve prolapse repair using FE modeling methods. Future studies will examine the effects of leaflet resection type as well as annuloplasty ring size and shape.**

(Ann Thorac Surg 2014;97:1496–504)
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Degenerative mitral valve (MV) disease is the most common cause of MV disease in the United States and mitral prolapse is its most common manifestation [1]. Mitral regurgitation (MR) associated with degenerative disease is progressive and most commonly caused by either a new flail leaflet or progressive increase in annular diameter or both [2]. Mitral valve repair for severe MR is indicated in patients with symptoms and systolic dysfunction, and asymptomatic patients in whom repair is likely to succeed [3]. Operative mortality and initial correction of MR is excellent after MV repair for degenerative disease.

There are, however, a number of significant problems with MV repair. First, mitral repair techniques are not standardized. For instance, mitral annuloplasty (MA) devices vary in shape and stiffness and MA sizing is inexact. In addition, MV prolapse was historically treated by leaflet resection but recently leaflet sparing neo-chord construction has been advocated. To date, results with leaflet resection and neo-chord application have been similar [4]. The low likelihood of mitral repair in this country (41% to 69% [5, 6]) is due to this lack of standardization and experience with significantly low individual surgeon and center volume. Second, recurrent 2 to 4+ MR after MV repair occurs at a rate of 2.6% per year, even after exclusion of patients with the more severe Barlow syndrome [7]. Reoperation rate progresses more slowly but reaches 20% at 19.5 years [8]. We believe that mitral repair durability is related to initial postoperative leaflet and annular geometry with subsequent leaflet remodeling due to stress.

Accepted for publication Dec 18, 2013.

*Authors Liang Ge and William G. Morrel are co-first authors.

Address correspondence to Dr Ratcliffe, Division of Surgical Services (112), San Francisco Veterans Affairs Medical Center, 4150 Clement St, San Francisco, CA 94121; e-mail: mark.ratcliffe@va.gov.

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Published by Elsevier Inc

0003-4975/$36.00
http://dx.doi.org/10.1016/j.athoracsur.2013.12.036

Abbreviations and Acronyms

A-P	=	anteroposterior
C-C	=	commissure-commissure
ED	=	end diastole
ES	=	end systole
FE	=	finite element
LV	=	left ventricle
MA	=	mitral annuloplasty
MI	=	myocardial infarction
MR	=	mitral regurgitation
MRI	=	magnetic resonance imaging
MV	=	mitral valve
NYU	=	New York University
TEE	=	trans-esophageal echocardiography
VR	=	virtual reality

The purpose of the current study is to create and validate an accurate finite element (FE) model of the MV and left ventricle (LV) using magnetic resonance imaging (MRI) and three-dimensional (3D) transesophageal echocardiography (TEE) obtained in a single patient with degenerative MV disease. After validation, models will be used to calculate the effect of triangular resection and MA on leaflet stress and annuloplasty suture force. We tested the hypothesis that postoperative MV leaflet and annular stress are increased after MV repair.

Material and Methods

Mitral Valve Repair

The single MV procedure studied was performed at New York University. The study protocol was approved by the New York University Institutional Review Board. Subsequent analysis of de-identified radiographic images obtained from the patient was judged exempt by the Committee on Human Research of the University of California, San Francisco.

Imaging

MAGNETIC RESONANCE IMAGING. Cardiac imaging was performed using a GE 1.5 Tesla scanner (General Electric Healthcare, Waukesha, WI). Electrocardiogram-gated cine images of the heart were acquired. A series of long and short-axis images of the LV were obtained in which slices were oriented perpendicular to or along the long axis of the LV.

THREE-DIMENSIONAL ECHO. After induction of anesthesia, 3D TEE was performed by an attending cardiologist specializing in echocardiography (Fig 1). The standard 20 views of the heart recommended by the American Society of Echocardiography/Society of Cardiovascular Anesthesiologists Guidelines [9] were obtained with a focus on the mitral valve anatomy and LV function. Next, multiple 3D images were obtained of the mitral valve and subvalvular apparatus in addition to images of the proximal LV. During acquisition of 3D full volume images respiration was held and any movement to the patient was paused to avoid stitch artifacts. Two-dimensional and 3D images were obtained both pre-repair and post-repair off cardiopulmonary bypass.

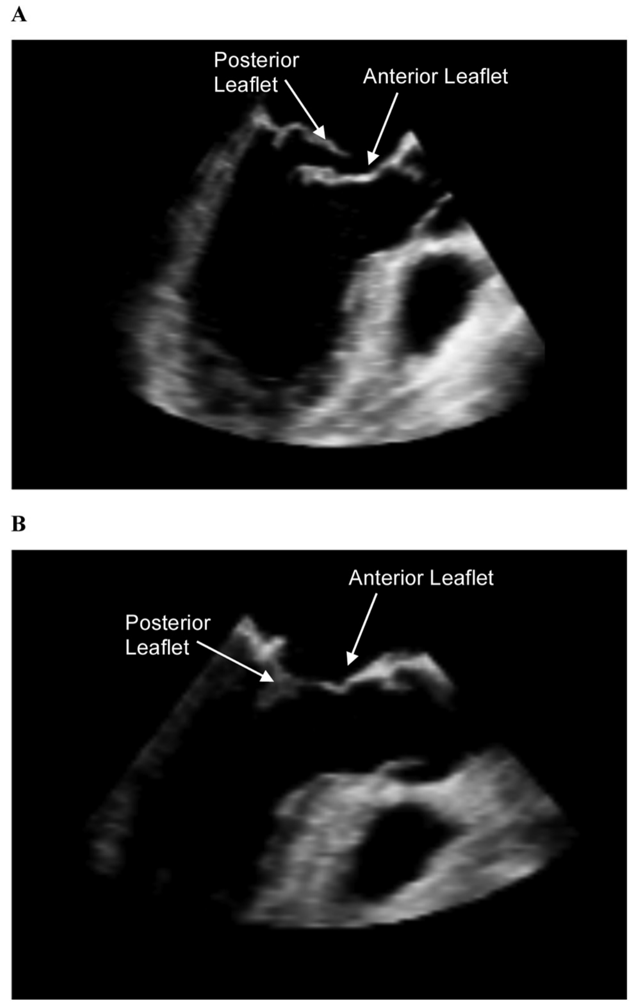

Fig 1. (A) Preoperative transesophageal echocardiography (TEE) and (B) postoperative TEE.

Image Analysis

Images were de-identified (Santesoft DICOM editor, Santesoft LTD, Athens, Greece). The MRI and 3D TEE images of the heart were manually co-registered by aligning the ventricular wall and papillary muscles from the 2 modalities using the medical image processing environment MeVisLab (v 2.1, MeVisLab, Bremen, DE).

The 3D TEE and MRI images obtained at early diastole were manually co-registered. Specifically, the LV long axis, defined as the line between the LV apex and middle of the anterior mitral annulus, in both 3D TEE and MRI was rotated into the Z axis. The 3D TEE image was then manually translated and rotated until papillary muscles and mitral annulus were superimposed.

The endocardial and epicardial surfaces of the LV and the anterior and posterior mitral valve leaflets were manually contoured. End diastole and end systole were

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