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Automated quantification of mitral valve anatomy using anatomical intelligence in three-dimensional echocardiography

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ABSTRACT

Background: Quantitative analysis of mitral valve morphology with three-dimensional (3D) transesophageal echocardiography (TEE) provides anatomic information that can assist clinical decision-making. However, routine use of mitral valve quantification has been hindered by tedious workflow and high operator-dependence. The purpose of this paper was to evaluate the feasibility, accuracy and efficiency of a novel computer-learning algorithm using anatomical intelligence in ultrasound (AIUS) to automatically detect and quantitatively assess the mitral valve anatomy.
Methods: A novice operator used AIUS to quantitatively assess mitral valve anatomy on the 3D TEE images of 55 patients (33 with mitral valve prolapse, 11 with functional mitral regurgitation, and 11 normal valves). The results were compared to that of manual mitral valve quantification by an experienced 3D echocardiographer and, in the 24 patients who underwent mitral valve repair, the surgical findings. Time consumption and reproducibility of AIUS were compared to the manual method.
Results: AIUS mitral valve quantification was feasible in 52 patients (95%). There were excellent agreements between AIUS and expert manual quantification for all mitral valve anatomic parameters ($r = 0.85$–0.99, $p < 0.05$). AIUS accurately classified surgically defined location of prolapse in 139 of 144 segments analyzed (97%). AIUS improved the intra- [intraclass-correlation coefficient (ICC) = 0.91–0.99] and inter-observer (ICC = 0.86–0.98) variability of novice users, surpassing the manual approach (intra-observer ICC = 0.32–0.95; inter-observer ICC = 0.45–0.93), yet requiring significantly less time (144 ± 24 s vs. 770 ± 89 s, $p < 0.0001$).
Conclusion: Anatomic intelligence in 3D TEE image can provide accurate, reproducible, and rapid quantification of the mitral valve anatomy.

1. Introduction

Mitral regurgitation is the most common form of valve dysfunction in industrialized countries [1]. Correct assessment of the mitral valve anatomy is crucial for surgical repair and catheter-based intervention planning. Three-dimensional (3D) transesophageal echocardiography (TEE) has been shown to be valuable for providing accurate, qualitative information of the mitral valve, such as locations of the leaflet pathology, surpassing 2D TEE [2].

The increasingly complex techniques used in mitral valve surgery and catheter-based procedures demand more sophisticated, quantitative assessment of the mitral valve anatomy. Recent studies suggested that quantitative mitral valve characteristics including annular anteroposterior diameter, commissural width, and posterior leaflet height, as assessed by 3D TEE, provided incremental information and predicted the complexity of mitral valve repair [3]. Moreover, quantification of the leaflet prolapse height and volume, as well as the annular height and non-planarity index, provides important information

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regarding the etiologies and pathophysiology of mitral regurgitation [4–6], potentially assisting diagnosis [7,8] and guiding treatment [9]. However, most of these studies involved operators that are highly experienced in performing mitral valve quantification on 3D echocardiography. The process requires operators that are familiar with the many variations of the mitral valve normal anatomy and pathology in order to have the anatomic markers placed at the correct positions consistently. Therefore, substantial measurement bias and variability can potentially be introduced by inexperienced operators [10]. Moreover, the manual mitral valve quantification process is very labor-intensive and time-consuming [11]. As a result, although being able to provide additional, clinically important information, mitral valve quantification has not been adopted routinely in mitral valve assessment.

"Anatomical intelligence in ultrasound (AIUS)" is the phrase used to describe the process where an ultrasound device automatically adapts images based on individual patients' anatomical variation [12]. It is a form of machine learning that encompasses an understanding of anatomic structure allowing automatic detection of anatomic landmarks with minimal manual input. This process enhances reproducibility and reduces analysis time for complex tasks such as mitral valve quantitative assessment. Accordingly, the aims of the present study were (1) to evaluate the agreement of AIUS mitral valve quantification with the results of expert manual measurements, and (2) compare the reproducibility and efficiency between the AIUS and manual methods for mitral valve quantification.

2. Methods

2.1. Patient population

Three-D TEE images of the mitral valve acquired from 55 consecutive patients, including 33 patients with mitral valve prolapse, 11 patients with functional mitral regurgitation, and 11 normal subjects, were analyzed. Clinical indication for TEE included evaluation of mitral regurgitation, preoperative assessment of mitral valve reparability, exclusion of suspected endocarditis, and evaluation of cardiac source of embolism. Mitral valve prolapse was defined as systolic displacement (>2 mm) of 1 or both mitral leaflets into the left atrium, below the plane of mitral annulus, as indicated in the 2D parasternal long-axis view. Functional mitral regurgitation was diagnosed when mitral regurgitation was associated with left ventricular global or regional dysfunction without intrinsic mitral valve structural abnormalities. The severity of mitral regurgitation was quantified by calculating the effective regurgitant orifice area using the proximal flow convergence method [13]. Informed consent was obtained from each patient. The study protocol conforms to the ethical guidelines of the 1975 Declaration of Helsinki as reflected in a priori approval by the institution's human research committee.

2.2. Image acquisition

Three-D TEE of the mitral valve was performed with an EPIQ7 or iE33 ultrasound system (Philips Healthcare, Andover, MA) equipped with a fully sampled matrix transducer (X7-2t). Zoomed 3D TEE images of the mitral valve apparatus were acquired. The region of interest was adjusted to the smallest pyramidal volume that encompassed the mitral valve, with multi-beat (if the patient was in sinus rhythm) or high volume rate (if in atrial fibrillation) acquisition, to maximize temporal resolution (>15 Hz). Acquisition of 3D data sets was repeated several times to ensure optimal image quality without stitching artifact. All TEE images were acquired by an experienced echocardiographer (American Society of Echocardiography level 3).

2.3. Mitral valve quantification

All 3D images were analyzed offline using both manual (MVQ, QLAB 9; Philips Healthcare) and AIUS software packages (MVN$^{A.I.}$, QLAB 10; Philips Healthcare), each installed on one of two independent

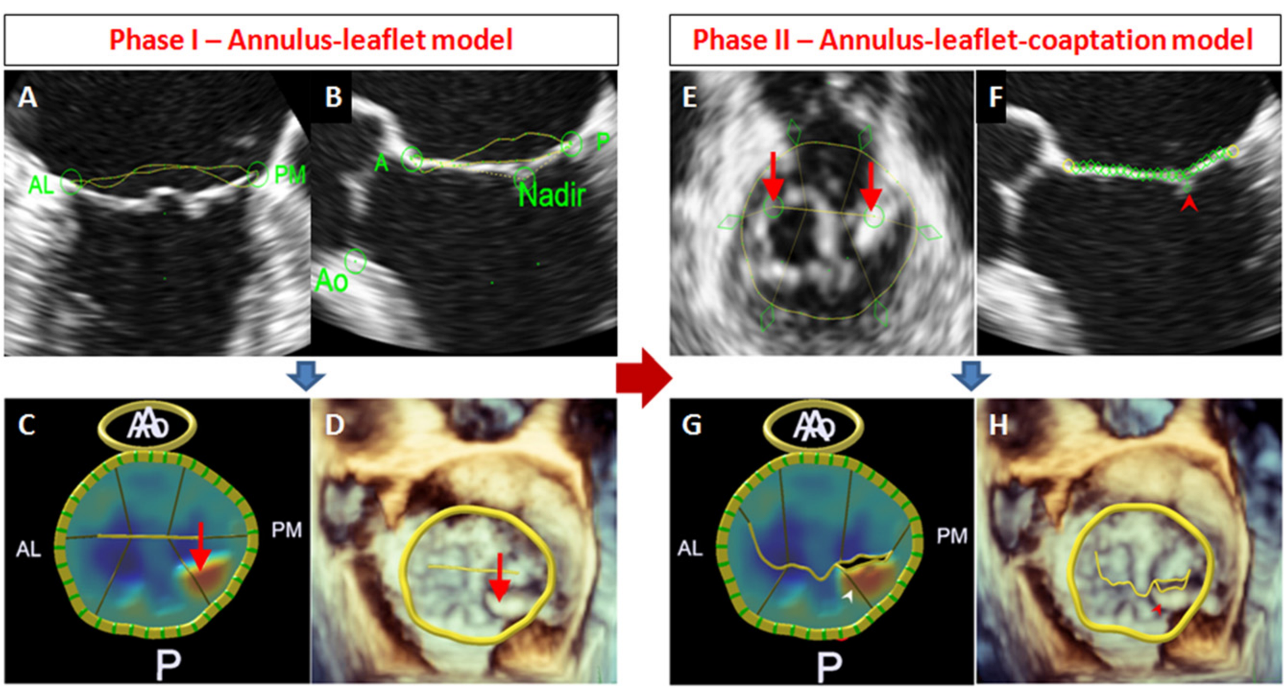

Fig. 1. Mitral valve quantification process using anatomical intelligence in ultrasound. A–D: anterolateral (AL), posteromedial (PM), anterior (A), and posterior (P) mitral annulus points; aortic annulus (Ao); and coaptation (Nadir) points were tagged in the 2 orthogonal long-axis planes (A and B). Then, a color-coded 3-dimensional topographical surface is displayed with leaflet billowing above the annular plane (minimal surface) depicted red (arrow) and leaflet below the annular plane blue (C). The surgeon's view of mitral valve with automatically tracked annular contour (yellow line) superimposed on the volume-rendered image showing P3 scallop billowing (arrow) (D). E–H: the two commissures were marked in the short-axis plane (arrows) (E). Points of leaflet coaptation (arrow) were marked plane by plane from commissure to commissure to delineate the line of coaptation (F). The final mapping is displayed as a color-coded topographical map (G) and annular contour (yellow line) with the line of coaptation superimposed on the volume-rendered image showing P3 scallop prolapse with involvement of the leaflet edge (arrow) (H).