Computers and Mathematics with Applications 68 (2014) 1569–1580

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

journal homepage: www.elsevier.com/locate/camwa

Echocardiographic particle imaging velocimetry data assimilation with least square finite element methods

Prathish K. Rajaraman [a], T.A. Manteuffel [b], M. Belohlavek [c], E. McMahon [c], Jeffrey J. Heys [a,*]

[a] Chemical and Biological Engineering Department, Montana State University, Bozeman, MT 59717, United States
[b] Department of Applied Mathematics, University of Colorado, Boulder, CO 80309, United States
[c] Mayo Clinic Arizona, Scottsdale, AZ 85259, United States

ARTICLE INFO

Article history:
Available online 22 August 2014

Keywords:
Least-square
Finite element
Data assimilation
Particle imaging velocimetry

ABSTRACT

Recent developments in the field of echocardiography have introduced various noninvasive methods to image blood flow within the heart chambers. FDA-approved microbubbles can be used for intracardiac blood flow imaging and determining the velocity of the blood based on the displacement of the bubbles and the frame rate of the ultrasound scan. A limitation of this approach is that the velocity field information is only two-dimensional and inevitably contains noise. A weighted least square finite element method (WLSFEM) was developed to assimilate noisy, two-dimensional data from echocardiographic particle imaging velocimetry (echo-PIV) into a three-dimensional Navier–Stokes numerical model so that additional flow properties such as the stress and pressure gradient can be determined from the full velocity and pressure fields. The flexibility of the WLSFEM framework allows for matching the noisy echo-PIV data weakly and using the weighted least square functional as an indicator of how well the echo-PIV data are satisfying the numerical model. Results from the current framework demonstrate the ability of the approach to more closely match the more accurate echo-PIV data and less closely match the noisy data. The positive impact of assimilating the echo-PIV data is demonstrated: compared to a conventional computational fluid dynamic approach, echo-PIV data assimilation potentially enables a more accurate flow model.

1. Introduction

The efficient flow and pumping of blood in the left ventricle of the heart is critical for overall health [1–3]. In recent years, many researchers and scientist have made significant progress towards a better understanding of efficient blood flow in the left ventricle, including the development of imaging techniques and computational fluid dynamics (CFD) models [1,4–6]. Each method, imaging and simulation, carries its own advantages and disadvantages. For example, magnetic resonance imaging (MRI) is expensive and confines the patient to a limited space and immobile position to obtain an imaging sequence of the flow in the heart, whereas ultrasound imaging, in comparison, is less expensive and restrictive, but provides anatomic images with lesser fidelity although with higher temporal resolution. The common advantage of imaging techniques, compared to CFD models, is obtaining patient-specific data [2,3,5,6]. The advantage of a CFD model is the ability to provide

* Correspondence to: Chemical and Biological Engineering Department, Montana State University, Box 173920, Bozeman, MT 59717, United States. Tel.: +1 406 994 7902.
E-mail addresses: jeff.heys@gmail.com, jeffrey.heys@coe.montana.edu (J.J. Heys).

http://dx.doi.org/10.1016/j.camwa.2014.07.026
0898-1221/

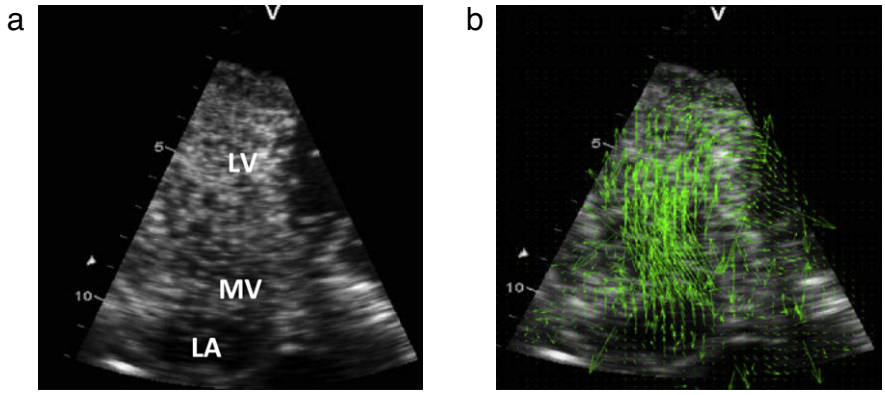

Fig. 1. An ultrasonogram of the left ventricle (LV), mitral valve (MV), and left atrium (LA) after injecting microbubbles (a). The corresponding echo-PIV data (velocity vectors) (b).

a virtual environment in which ranges of fluid parameters (e.g., blood viscosity) and geometric features can be explored without jeopardizing patient safety thus facilitating better understanding of the physics of cardiac functioning as a pump. However, CFD models can include physical assumptions and are rarely patient-specific. Another limitation of CFD models is that they are never perfect in the sense that they do not capture all of the physics, chemistry, and biology of a real heart.

Many investigators and clinicians are in need of a framework that combines the strengths of both a CFD model and patient-specific imaging. This framework would allow assimilation of patient-specific data into a CFD model to enable realistic replication of cardiac fluid dynamic properties and, thus, further improvement in diagnosis and prognosis of cardiac disease [1]. Methods have been developed that enable data obtained from experimental measurements to be assimilated (or integrated) into a computational model [1,2,7]. Challenges associated with previously developed methods, however, make those methods impractical for the problem of interest here. For example, many data assimilation approaches use the Kalman filter that requires an ensemble of approximate solutions, which increases the computational cost dramatically [2,8]. Other approaches incorporate experimental data points at arbitrary spatial locations by smoothing and interpolating the experimental data to computational nodes, but the interpolation can compromise the accuracy of the experimental data [1,2,7]. The approach described here is based on the weighted least-square finite element method (WLSFEM), which reduces computational costs relative to ensemble approaches and is able to assimilate an arbitrary number of data points into the simulation from arbitrary spatial locations without any interpolation or smoothing of the data [2].

The WLSFEM framework allows for the simulation of blood flow in the cardiac left ventricle and assimilates experimental data obtained using echocardiographic particle imaging velocimetry (echo-PIV). The echo-PIV method utilizes FDA approved microbubbles injected into the blood stream. Imaging of the left ventricle by cardiac ultrasonography determines microbubble location [1,2,7]. In recent years, the echo-PIV technique has been studied extensively in both experimental and clinical settings [9]. The images obtained by ultrasonography can be assessed by a number of available PIV analysis algorithms. PIVlab, an open source software algorithm for calculating particle (i.e., microbubble) velocity based on its displacement over a time period between successive image frames [10], is used here to obtain flow velocity vectors inside the left ventricle.

Fig. 1(a) depicts the left ventricle during an experimental study with microbubbles (appearing as white spots). The ultrasound probe scans from the apex of the heart (i.e., top of the sector image). Fig. 1(b) shows a velocity vector field reconstructed from the corresponding echo-PIV, and we can identify misdirected, i.e., noisy, velocity vectors. Because sufficient temporal resolution (i.e., >100 frames/s) is currently technologically limited to 2-dimensional scans, PIV analysis only provides two components of 3-dimensional velocity vectors (the two components are tangential to the plane of the original image). These are still valuable blood flow velocity data, but additional flow properties, such as the pressure gradient and viscous energy losses, would be of a great clinical value but cannot be computed from the 2-dimensional vector fields [1,2]. The desired flow information, especially pressure gradients and stresses, requires that the full 3-dimensional velocity fields be known. At this point, the reader may ask why not use other methods to obtain the full three dimensional velocity field, such as an MRI approach? MRI machines are expensive and patients need to be sedated before the scan in order to prevent them from moving, which often leads to side effects such as headaches and nausea [9]. Further, MRI imaging often lacks the temporal accuracy required for some of the desired flow properties. The 3-dimensional data obtained from MRI are time-averaged over several cardiac cycles, which prevent the capture of a real-time flow pattern [9]. The echo-PIV method is attractive because it is inexpensive, broadly available, has a high temporal resolution, and the microbubble injection procedure is minimally invasive [1,2,9].

The current paper builds upon our previous publication [2], but focuses on assimilation of data from a significantly larger number of time steps and a higher temporal resolution (a more than one order of magnitude increase in both time and space). In the current paper, we have also employed a much more realistic geometry for the left ventricle, which is more demanding on meshing and has required implementation of higher-order tetrahedral elements [11]. In the previous paper, the weighting of the echo-PIV data was mostly arbitrary, because it was based on the accuracy of a different PIV approach—