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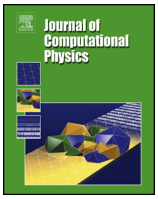

Computational modeling of cardiac hemodynamics: Current status and future outlook

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ABSTRACT

The proliferation of four-dimensional imaging technologies, increasing computational speeds, improved simulation algorithms, and the widespread availability of powerful computing platforms is enabling simulations of cardiac hemodynamics with unprecedented speed and fidelity. Since cardiovascular disease is intimately linked to cardiovascular hemodynamics, accurate assessment of the patient's hemodynamic state is critical for the diagnosis and treatment of heart disease. Unfortunately, while a variety of invasive and non-invasive approaches for measuring cardiac hemodynamics are in widespread use, they still only provide an incomplete picture of the hemodynamic state of a patient. In this context, computational modeling of cardiac hemodynamics presents as a powerful non-invasive modality that can fill this information gap, and significantly impact the diagnosis as well as the treatment of cardiac disease. This article reviews the current status of this field as well as the emerging trends and challenges in cardiovascular health, computing, modeling and simulation and that are expected to play a key role in its future development. Some recent advances in modeling and simulations of cardiac flow are described by using examples from our own work as well as the research of other groups.

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1. Introduction

Among all diseases, cardiovascular disease (CVD) remains the leading cause of mortality (about 33%) in the US. In 2012, the incidence of CVD in adults aged ≥ 20 years was 35% and about 800,000 deaths were attributed to CVD [1]. While improvements in diagnosis and treatment have led to improved outcomes and reduced rate-of-mortality since the 1970s, other trends associated with CVD point to a troubling future (see Fig. 1(a)). CVD has a strong correlation with age and by 2050, more than 40% of the population (about 200 million adults) will be ≥ 45 years old. Heart disease also has a positive correlation with obesity and since 1980, the percentage of adults aged 20–74 who are considered clinically obese, has doubled to more than 30% [1]. CVD also has a positive correlation with diabetes, the incidence of which is also growing

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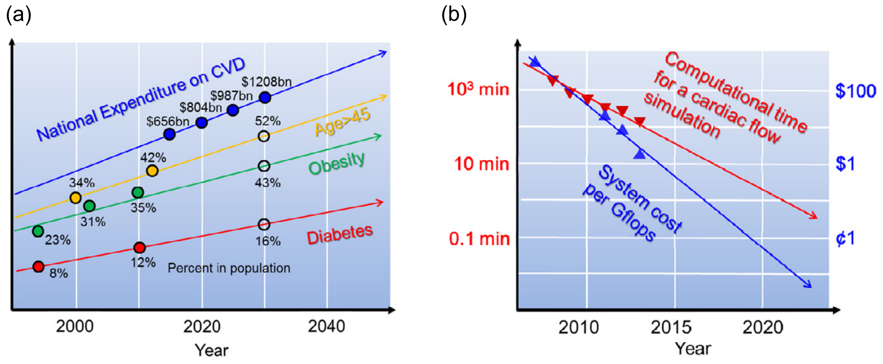

Fig. 1. (a) Trends in the cardio vascular disease [1], http://www.census.gov/population/age/. (b) Trends in computational speed and cost with time. Computational time for a cardiac simulation is estimated for a simulation with 25 million grid points which requires approximately 1 ExaFLOP on a world #500 cluster (http://top500.org/statistics/perfdevel/). System cost per a Gflops is based on http://en.wikipedia.org/wiki/FLOPS.

steadily with time. Additionally, CVD ranks highest in terms of national healthcare expense with close to half a trillion dollars spent on this in 2010; this is more than twice the health expenditures on cancer, which is the next most expensive disease [1]. The high healthcare cost of CVD is due not only to its prevalence in the population, but also to the cost of the treatment; the mean hospital charge for a CVD procedure was close to sixty thousand dollars in 2010 [1] and these costs are projected to rise faster than the cost-of-living in the foreseeable future. While the numbers reported here are for the US, the trends are not very different for the world population at large. Many of these costs result from under-treatment or over-treatment and often a reliance on costly invasive procedures that may or may not improve downstream outcomes.

Thus, improvements in diagnosis and the guidance of proper therapies (medical and/or invasive) are required to deliver cost-effective treatments to patients. However, many examples are available where outcomes may be improved in some, but not all patients by using technology that is very expensive. For example, cardiac resynchronization therapy with biventricular pacemakers aimed at improving cardiovascular hemodynamics, is a costly therapy that results in approximately 11–46% of the recipients deriving no benefit [2]. In the case of CVD that alters cardiac hemodynamics, the only way to tackle this burgeoning crisis is to develop technologies that accurately characterize cardiac hemodynamics and enable better selection of patients for costly invasive versus less costly medical therapies. The key is to develop technologies that improve treatment outcomes without concurrently increasing the cost of diagnosis and treatment.

One way to tip the scales in our favor is to counteract these unfavorable trends with ones that are favorable, and one trend that is significantly in our favor is the Moore's Law [3], which refers to the trend in computing, enabled by increases in clock-speed, concurrency, memory and memory bandwidth, that has continuously enabled ever-larger, faster and cheaper computations. Some of the largest supercomputers today reach speeds in the PFLOPS (Peta FLoating-point Operations per Second) but a thousand-fold increase to 10^{18} FLOPS or ExaFLOPS (EFLOPS) is expected in less than 10 years. In addition to the speed of computation, the cost of computation is also an important factor when considering applications to medical therapy and diagnostics. In this regard, it has been noted that the cost per FLOP has also been cut by roughly 50% each year; a trend which is also expected to continue into the future (Fig. 1(b)). Commoditization of computational resources through virtualization and cloud-computing will further accelerate cost reductions and make high-performance computing ubiquitous.

From the point-of-view of computational modeling, it is useful to separate cardiovascular hemodynamics into cardiac hemodynamics (blood flow in the left and right ventricles and atria of the heart) and vascular hemodynamics (blood flow in the vessels that transport blood to and from these chambers to the rest of the body). The latter, i.e. computational modeling of vascular hemodynamics is a relatively mature field especially for larger vessels that are well resolved by medical imaging (e.g. aorta and main branches of coronary arteries). The simulations of blood flow in these larger vessels are becoming more reliable by coupling with lumped elements models [4,5] of the circulatory system and the smaller vessels. There are numerous examples where such modeling has either reached or will soon reach translation to clinical applications [6,7]. An excellent example in this regard is the CFD-based protocol for the assessment of the functional significance of coronary artery stenoses developed by HeartFlow [7], which recently been approved by FDA for clinical use. Other examples in vascular hemodynamics, where CFD modeling has advanced significantly towards clinical application include optimization of the Fontan procedure [8,9] and treatment of Kawasaki disease [10].

The current article, however, focuses on computational modeling of *cardiac* hemodynamics, i.e. the flow in the chambers of the heart (see Fig. 2), which presents some different challenges for computational modeling and which, due to these challenges, is further away from clinical application. These challenges are primarily due to the large-scale motion and complex deformation of the chambers (the LV for instance changes its volume by almost 100% of the end-systolic volume in every cardiac cycle), complex flow-induced dynamics of the valves and a higher flow Reynolds number which induces transition to turbulence.

The present article is organized as the following. In section 2, the potential clinical applications of cardiac simulations and the required computational performance is discussed. In section 3, the recent advances in cardiac simulation and the

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