Assessing relative energy loss across heart valves using generalized phase-contrast flow measurements

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Introduction:

Pathological flow conditions may cause turbulence and hence energy dissipation. For example, in diseased or artificial aortic valves regurgitant flow and energy losses due to turbulent flow patterns may compromise the efficiency of the circulatory system and, accordingly, increase cardiac load. As a consequence, remodeling may occur, and at an advanced state, cardiac failure is expedited. Conventional measures of valve performance rely on assumptions about the relationship between increased work load and parameters which are not directly connected to energy losses [1]. Therefore, there is a need for a direct measurement of energy loss relative to the total energy the heart generates.

The concept of quantifying turbulence using Phase-Contrast MRI has already been introduced more than 20 years ago [2], but only recent studies have demonstrated feasibility in vivo [3]. In the present work a method to quantify energy losses relative to the total energy of the flow is proposed thereby providing patient-specific normalization accounting for individual differences in cardiac performance.

$$Rel.\,energy\ losses = \frac{TKE \cdot voxelsize_{z-dir.}}{MKE} + \frac{MKE_{Reflow}}{MKE} \qquad \textbf{eq. 1}$$

Materials and Methods:

Time-resolved 3D Phase-Contrast flow measurements with multiple first gradient moments were employed to quantify velocities and turbulence intensities over a large dynamic range. Measurements with 3 different encoding steps in each direction were combined using a Bayesian analysis method [4,5] to estimate the 4D velocity vector field and turbulent kinetic energy (TKE) as proposed in [3]. Energy losses were calculated by relating TKE to the mean kinetic energy (MKE) normalized by the voxel size in flow direction, and by relating regurgitant to forward flow (**eq. 1**). For computation of the TKE values, the whole volume was considered. For MKE quantification a region downstream from the valve was taken assuming laminar flow conditions. Slices in flow direction were averaged to obtain a single-value readout (**Fig. 1a**).

In-vitro measurements were performed using a home-built pulsatile flow phantom equipped with a mechanical St. Jude Medical Standard bileaflet valve (St. Jude Medical Inc., St. Paul, MN, USA) or a biological Transcatheter Medtronic CoreValve (Medtronic Inc., Minneapolis, MN, USA). In vivo data were acquired in 6 healthy volunteers and two patients with a stenotic valve (valve area 0.9 cm^2, mean gradient 34 mmHg) and a Medtronic CoreValve, respectively.

All data were acquired on a 3T Achieva system (Philips Healthcare, Best, The Netherlands) with cardiac triggering and navigator gating. The voxel size was 2 mm isotropic and temporal resolution was 34 ms. Using 8-fold k-t undersampling and k-t PCA reconstruction [6], scan time was 8 min without taking into account navigator efficiency.

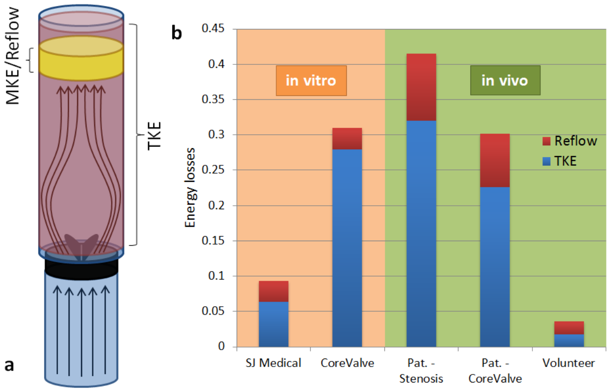

Fig. 1: a) Schematic of flow in the phantom setup and regions for MKE-/TKE calculation. b) Comparison of the results of in vitro and in vivo measurements.

Results:

Fig. 1b shows the comparison of the relative energy losses due to turbulence and regurgitation in-vitro and in-vivo. It is seen that relative energy losses differ significantly for the patient and volunteer population but also for the different valve designs tested. Exemplary streamline visualization of the flow and isosurface rendering of TKE values in a volunteer and both patients is shown in **Fig. 2**. Maximum TKE values in volunteers were 149±12 J/m^3. In patients maximum TKE values were significantly higher at 950 J/m^3 and 540 J/m^3 for the stenotic and the artificial valves, respectively. Patient stroke volumes were 68 ml and 80 ml while volunteer stroke volumes ranged from 72 to 84 ml.

Discussion:

In this work a method for direct assessment of energy losses associated with different flow conditions has been proposed. It was demonstrated that measurements in vitro as well as in vivo are feasible and significant differences between valve designs and between diseased and healthy subjects exist. Without having to rely on assumptions of geometrical relationships and flow parameters, the notion of relative energy loss potentially provides a more accurate estimation of cardiac work load compared to previous methods. While the study of flows across heart valves has been demonstrated here, the proposed concept may well extend to other vascular territories and hence holds considerable promise for assessing the hemodynamic state in larger vessels.

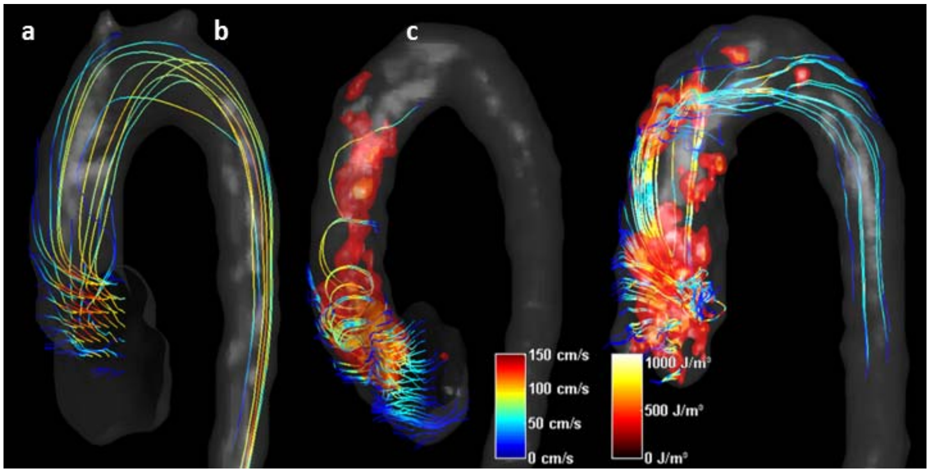

Fig. 2: Streamlines and turbulent kinetic energy in the aortic arch of a) a healthy volunteer, b) a patient with a stenotic aortic valve, and c) a patient with a CoreValve implanted. The colors of the streamlines correspond to velocities, and the isosurfaces to different levels of TKE. There are no TKE isosurfaces visible in the data of the healthy volunteer given identical scaling across all examples.

References:

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