The characterisation of blood rotation in a human heart chamber based on statistical analysis of vorticity maps

Kelvin K.L. Wong[a,c], Richard M. Kelso[b], Stephen G. Worthley[c], Prashanthan Sanders[c], Jagannath Mazumdar[a] and Derek Abbott[a]

[a]Center for Biomedical Engineering and School of Electrical & Electronics Engineering, University of Adelaide, SA 5005, Australia;
[b]School of Mechanical Engineering, Sports Engineering Group, University of Adelaide, SA 5005, Australia;
[c]Cardiovascular Research Centre and School of Medicine, University of Adelaide, SA 5005, Australia

ABSTRACT

Modelling of non-stationary cardiac structures is complicated by the complexity of their intrinsic and extrinsic motion. The first known study of haemodynamics due to the beating of heart was made by Leonardo Da Vinci, giving the idea of fluid-solid interaction by describing how vortices develop during cardiac structural interaction with the blood. Heart morphology affects in changes of cardio dynamics during the systolic and diastolic phrases. In a chamber of the heart, vortices are discovered to exist as the result of the unique morphological changes of the cardiac chamber wall by using flow-imaging techniques such as phase contrast magnetic resonance imaging. The first part of this paper attempts to quantify vortex characteristics by means of calculating vorticity numerically and devising two dimensional vortical flow maps. The technique relies on determining the properties of vorticity using a statistical quantification of the flow maps and comparison of these quantities based on different scenarios. As the characteristics of our vorticity maps vary depending on the phase of a cardiac cycle, there is a need for robust quantification method to analyse vorticity. In the second part of the paper, the approach is then utilised for examining vortices within the human right atrium. Our study has shown that a proper quantification of vorticity for the flow field can indicate the strength and number of vortices within a heart chamber.

Keywords: Vorticity, Phase contrast magnetic resonance imaging, Histogram, Segmentation

1. INTRODUCTION

A phase contrast magnetic resonance imaging (MRI) approach is used in this study for the flow imaging of right atrium in a healthy subject. The use of this velocity-encoded MR imaging method applied onto cardiac imaging of right atria enables a good assessment of vortices that exist in the cardiac chamber. Phase contrast MRI can produce cine-MR images that are presented in a movie. It is a non-invasive imaging technique that allows study of flow-related physiology and pathophysiology with good spatial and temporal resolutions.

Velocity-encoded (VENC) phase contrast MRI allows three dimensional MR velocity mapping based on the intrinsic sensitivity of MRI to flow, and enables the acquisition of spatially registered functional information simultaneously with morphological information.[1] Three dimensional MRI based velocity mapping operates by registering three separate flow-sensitive volumes in the x, y and z orientations of the scan. The flow velocities may be computed by determining the shift of phase pertaining to the collection of imaged blood proton spins and reconstructing the flow vectors in advanced visualisation packages. This concept has varying terminologies in literature: the most common being phase contrast MRI, while some studies labelled it as phase-velocity MRI.[2] In general, such MRI based techniques form a class of approach known as magnetic resonance

Further author information: (Send correspondence to K.K.L. Wong)
K.K.L. Wong: E-mail: kwong@eleceng.adelaide.edu.au, Telephone: +61 (8) 8303 6296

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velocimetry (MRV) or sometimes also called magnetic resonance image velocimetry (MRIV). These techniques have been very commonly used for producing visualisation and investigation of flows even within non-organic structures.[3,4]

It has been widely documented that phase contrast MRI is a well established flow imaging scheme for cardiac examination of human subjects[2,5,6] in the arteries and aorta. Other cardiac structures such as the atria and ventricles have also been examined using this methodology.[7–10] We developed planar flow maps of blood flow in the right atrium of a healthy human subject and perform flow analysis using the tools we described in this paper. The initial stage involves performing phase contrast MRI of the heart at short axis through the atria. The blood motion can be mapped in two dimension based on combination of the velocity signal maps pertaining to two directions. Vorticity of flow is computed numerically and a vortex segmentation method is developed to break down the chamber flow region into sections that encapsulate each of the dominant vortex. Finally statistical analysis is executed based on each segregated vortex. We have identified two dominant vortices of opposite rotation in the right atrium for the initial time frames of one cardiac cycle.

This paper is organized as follows: Section 2 provides a description of the methodology which highlights the underlying concept of flow analysis based on cardiac flow. A system is developed to analyze the flow in the right atrium of a normal subject, and the phase contrast MR imaging details as well as parameters for analysis are described under Section 3. Section 4 provides the results of the flow analysis after vortex isolation and using statistical properties to characterize the vortices individually. The discussion of the results and success of the analytical framework is mentioned in Section 5. Finally, a conclusion of the methodology and flow results is presented in Section 6.

2. METHODOLOGY

This section describes the concepts of phase contrast magnetic resonance (MR) imaging modalities and a measurement framework to calculate rotational flow or vorticity and quantify this parameter statistically in order to implement a new visualization system for flow patterns in cardiac chambers.

2.1 Phase Contrast MRI Velocimetry

The phase contrast MRI technology is clinically attractive because it is able to provide quantitative information on blood flow without the need for contrast agent to be introduced into the human body. We present some images based on this MRI protocol in Figure 1. The phase contrast images are graphical representations of the velocity components (x- and y- directions) maps. The figure shows the Foot-Head (F-H) and Anterior-Posterior (A-P) orientation scans.

Combining the two velocity maps based on the in-plane x- and y- directions results in the velocity field of blood. Phase contrast MRI can be extended to three dimensions as well by combining an additional orientation, the Left-Right (L-R) image scans to obtain the through plane velocity component map. Then, having the z-velocity component in addition to the in-plane components will be possible.

As can be observed, phase contrast MRI encodes velocity information within the output images and we are able to decipher these data to produce velocity field maps for analysis of flow patterns within the cardiac chambers. The phase contrast framework enables the flow imaging of cardiovascular system non-invasively and with good reliability. This technology is well established in the medical imaging industry and will be able to serve as a gold standard flow imaging protocol for validation of new methodologies that will be developed.

2.2 Vorticity Measurement and Statistics of Flow Map

A definition of vorticity is provided by examining the magnitude of rotation of fluid about a specific examined point. This may be demonstrated by schematic elements in Figure 2(a). For numerical derivation of circulation, the summation of velocity vectors multiplied by the finite interval distance in the same direction and in the counter-clockwise direction around this point of measurement is performed. The vorticity ω is obtained by dividing the local circulation with the sampling or interrogation window that is the finite quantification of the area swept by this rotational flow. The vorticity is represented by a normal component of the in-plane flow which passes through the plane.

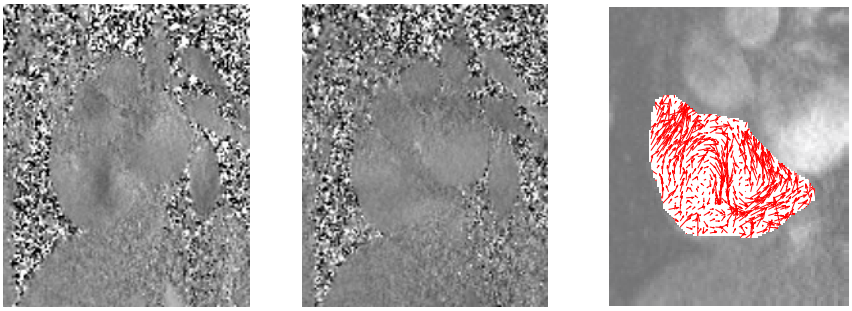
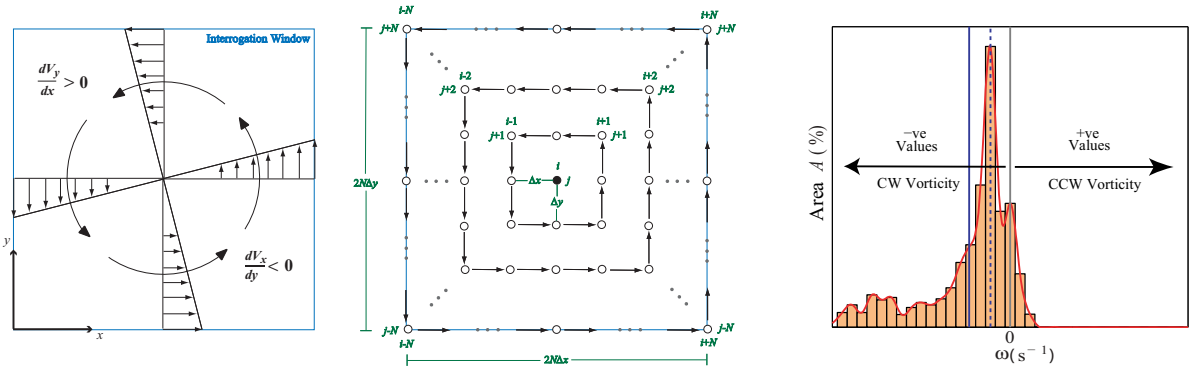


Figure 1: **Phase contrast images of cardiac chamber.** Short axis scans pertaining to time frames t=11 out of 30 frames in a cardiac cycle is presented. Scans based on two orientations, namely the Foot-Head (FH) and the Anterior-Posterior (AP) are taken. The intensity of the pixels in the image indicates the magnitude of the velocity component in the specified orientation. Combining two orthogonal velocity-encoded image maps can produce a two dimensional velocity flow field.

Note that in order to evaluate such integrals, an appropriate path or region of integration is to be chosen appropriately. Studies using boxes describing regions of interrogation often enclose the vortex core as the closed path for evaluating the fluid circulation.[11,12] From the formulation, positive values signify counter-clockwise (CCW) rotation, whereas negative values represent clockwise (CW) motion of the fluid.

We perform statistical quantification of the flow properties to characterise the vorticity distribution. The histogram that is produced based on the percentage of map area versus the vorticity values $\omega(s^{-1})$ throughout the entire flow map is featured in Figure 2(b). A high resolution of the histogram bins causes the histogram bar width to be overly small, and we propose the display of a frequency graph using a line that joins the height of each bar. In addition, we smooth the lines using spline interpolation to provide a more moderate estimation of the true frequency from each discrete bar height.



(a) Vorticity computation using finite elements

(b) Area A(%) versus vorticity $\omega(s^{-1})$

Figure 2: **Vorticity measurement and its histogram representation of the computed map.** Display of vorticity and calculations based on vectors along contour of flow around a node or usually a pixel in the flow vector image. Vorticity computation is based on the curl of vectors about a point of interest. Histogram depicting the variation of vorticity within the region of analysis gives an indication to the degree of rotation within the fluid. Flow investigations can be carried out by analyzing these histograms describing flow maps.

A quantification of average vorticity map value is computed by taking the mean $\overline{\omega}_\mu$ or median $\overline{\omega}_m$ of the frequency histograms that are generated from vorticity maps. The magntiude of these parameters is represented as the blue solid and dash lines, while the centre zero ω line is superimposed onto the frequency graph in

grey. The vorticity standard deviations from the flow map measures the relative scatter around the mean and median of the vorticity values in the map respectively. Standard deviation σ with respect to μ can be computed by considering the variation about the mean, and is denoted as σ_μ. Based on a similar mode of computation, calculating the degree of variation about the median will give σ_m.

2.3 Segmentation of Vortices for Analysis

This section describes the procedures for vorticity-based segmentation using *K*-means clustering and how analysis can be broken down into examination of individual vortex using histogram plots of the isolated vorticity region.

2.3.1 Color-Based *K*-Means Clustering Segmentation

Data clustering based on a color image is described here. The pixel classification is based on target colors in the segmentation. The technique of color image segmentation based on *K*-means clustering is applied. The number of clusters denoted by K affects the color differentiation as a large number of clusters may result in over-segmentation of the image and a small number will not enable sufficient region segregation.[13] The color quantization allows us to differentiate cluster regions which have unique class properties and therefore breakdowns the analysis into components.

We examine how the algorithm partition data into K clusters.[14] Assume that the feature vectors are denoted by $X = \{x_i | i = 1, 2, ..., n\}$. The generalized algorithm initiates K cluster centroids C, given that $C = \{c_j | j = 1, 2, ..., K\}$ and $K < n$, by randomly selecting K feature vectors from X. The feature vectors are quantized into each group labelled as j such that their Euclidean distances to the centroid of the group $D_j = ||x_i - c_j||$ are minimum given that $\forall \left(x_i, c_j\right) \epsilon X \times C$. The cluster centroids are computed again based on their group members and the new selection of the feature vectors according to the new cluster centroids is performed. The procedure terminates when there is no change in position of cluster centroids.

2.3.2 Segregation of Vortices

We now position two Oseen vortices with core centres at a distance of 5 mm apart from each other. The vortices have different polarities in rotation. This simulates flow consisting of two vortices overlapping partially. Each vortex is constructed in such as way that we computationally set the flow field to span 10 mm by 10 mm in space, and its maximum velocity magnitude to 10 mms^{-1}. Therefore, the maximum absolute velocity in the flow field map can reach up to 20 mms^{-1}. Note that the velocity field of this flow is represented by a digital image grid with a width of 160 and a height of 240 points matrix size.

From the results describing double vortices in the flow field (Figure 3 (a) and (b)), we are able to visually observe their cores and strength using vorticity flow maps. In addition, from the histogram pertaining to each flow map in Figure 3 (c), we can extract useful statistical properties that reveal some information about the flow scenario, such as the global polarities of vortices in the flow field.

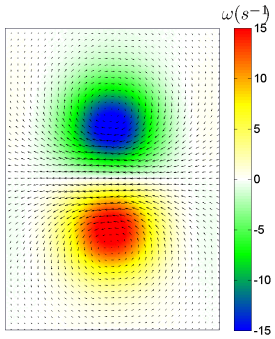
We can apply region segmentation of the vorticity map based on the proximity of similar map elements to determine the number of vortices that are present in a flow, and also to produce histogram plots of each distribution cluster(Figure 3 (d) to (i)). Using the *K*-means algorithm, we can determine regions with high intra-class and low inter-class similarities, whereby each set of regional clusters with such a characteristic is given a unique label. Therefore, we can localise vortices within the flow and provide a measure of discriminant measure based on the mean $\overline{\omega}$ and variance σ^2 of the cluster distribution. The discrimination of spatial separation for N number of vortices is given by

$$T = \frac{1}{N} \sum_{k=1}^{N} \frac{|\overline{\omega}_k|}{\sigma_k^2} \tag{1}$$

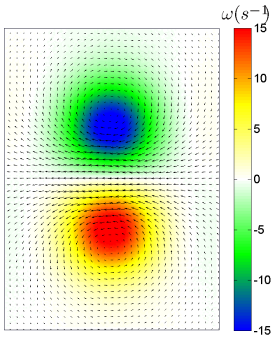
If T is large, it means that the vortices are defined with good intra-class similarities and inter-class dissimilarities. Figure 3 shows the results of applying segmentation on a pair of idealised Oseen vortices and examination of each segmented region using histogram plot of its vorticity distribution. Each homogeneous group of vorticity values is a representation of a vortex.

DOUBLE VORTICES

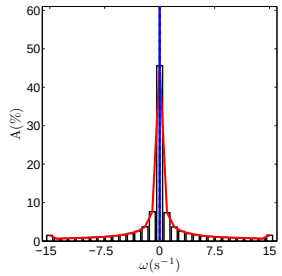
VELOCITY	VORTICITY	HISTOGRAM



(a) velocity plot



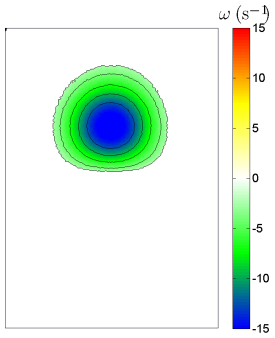
(b) vorticity plot



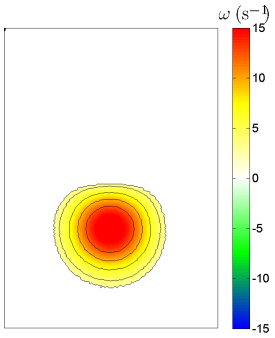
(c) histogram plot

VORTICITY PLOT COMPONENTS

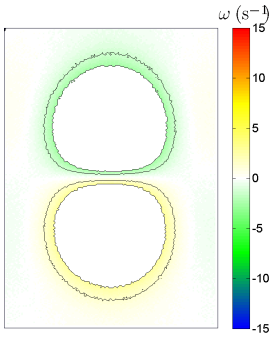
COMPONENT 1	COMPONENT 2	COMPONENT 3



(d) vorticity plot of component 1



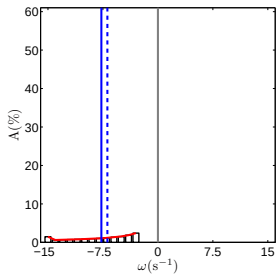
(e) vorticity plot of component 2



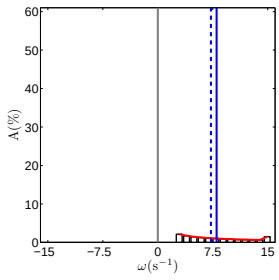
(f) vorticity plot of component 3

HISTOGRAM PLOT COMPONENTS

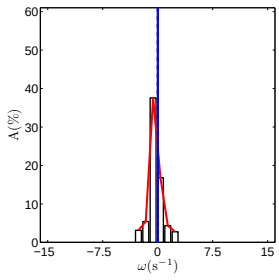
COMPONENT 1	COMPONENT 2	COMPONENT 3



(g) histogram plot of component 1



(h) histogram plot of component 2



(i) histogram plot of component 3

Figure 3: **Localisation and analysis of vortices.** Segmentation of flow field isolates the vortices and allows us to perform histogram analysis on its distribution. This enables breakdown of the analysis into components that can be quantified with more quantitative information. In this example, we have two Oseen vortices in a flow field and application of *K*-means algorithm segregates the flow region into three partitions. The histogram plot of each partition provides the mean and variance of the isolated vortex which can indicate its vorticity or speed of fluid rotation. Combining the segmented regions results in the same combination of their histograms.

3. EXPERIMENTS

3.1 Subject for Case Study

In this study, we performed flow imaging on the right atrium of a normal subject using phase contrast VENC flow imaging, and then using MR fluid motion tracking. The flow information from these two types of imaging can be used to explain the behaviour of vortices that develop in the right atrium of a heart.

Using a normal healthy male subject aged 22 years as our case study, we have examined the flow within chambers of his heart and the objective is to deduce if a single strong vortex exist in the right atrium, and understand its development over the cardiac cycle. This allows us to identify the principle features of the flow in a normal heart versus the abnormal one.

3.2 MRI Scan Procedure

The velocity-encoded MR imaging was performed using a Siemens Avanto, 1.5 Tesla, model-syngo MRB15 scanner with Numaris-4, Series No: 26406 software. Cine-MR imaging was performed using one slice in short axis views through the atria. All images were acquired with retrospective gating and 25 phases (from $t = 1$ to 25) for a single slice.

Phase contrast magnetic resonance imaging is used to scan the normal subject. Acquisition parameters include: echo time TR $= 47.1$ ms, repetition time TE $= 1.6$ ms, field of view FOV $= 298 \times 340$ mm at matrix of 134×256 pixels. We focus our examination on atrial flow visualisation in this experiment. This provides a useful way of viewing the entire development of the blood flow, instantaneously, to be able to obtain an understanding of vortex characteristics in the right atrium.

3.3 Investigation Procedure

A scan is performed at the section of the heart where the atria are positioned. This section is chosen such that the optimal display of the cross-sectional area of the right atrium is enabled. The larger the chamber size, the more accurate the tracking will be, since a larger number of track features, as a result of contrasting signal intensity due to asynchronous proton spins under magnetic resonance, will exist in a larger fluid space. The scan section is taken at a location whereby the scan is perpendicular to the axis joining the top of the heart to the apex through the septum.

4. RESULTS

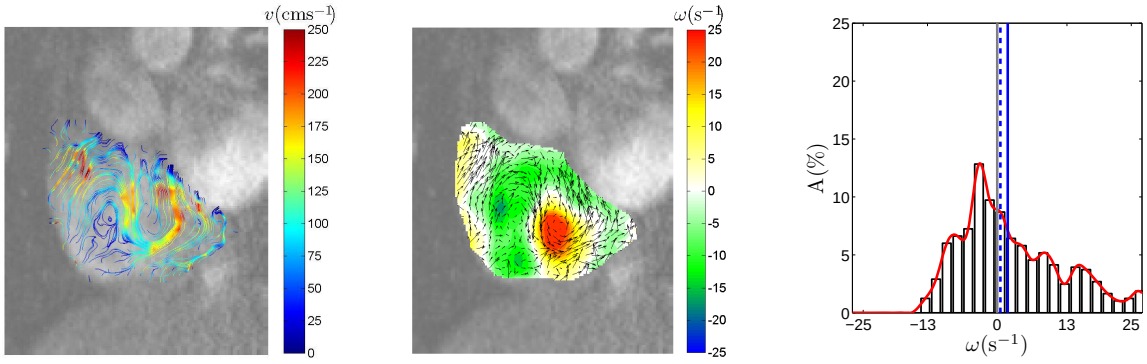
We observe the vortices that appear during the diastolic and systolic phases of the heart and analyse its course of development and changes over the cardiac cycle of phases. The change in polarity of rotation can be easily and visually observed using the streamlines, contour maps, and vector plots as shown in Figure 4. In addition, we have superimposed the corresponding MR images onto these flow fields to give an indication of the location of the vortex with respect to the chamber that it resides. A vorticity sampling mask of size (21×21) frame is used. This corresponds to (78.75×78.75) mm window size. The rectangular encapsulation of the displayed scan is (150.00×187.50) mm.

We present the flow results and analysis of the right atrium for the selected slice based on one time frame of the cardiac cycle using velocity and vorticity maps that can be statistically quantified. Histograms are computed for the vorticity map. Note that the mean and median of the histogram that are computed from the vorticity distribution are denoted by $\overline{\omega}_\mu$ and $\overline{\omega}_m$ respectively. Standard deviations with respect to the mean and median are denoted as σ_μ and σ_m respectively.

The intensity of vorticity using $\overline{\omega}_\mu$ and σ_μ gives a good estimation of the swirl structure in the right atrium. Based on our conventions, counter-clockwise and clockwise vorticity are represented in red and blue respectively on the contour map. Vortices in the atrium are shown to be dominantly counter-clockwise in rotation upon investigation.

NORMAL SUBJECT

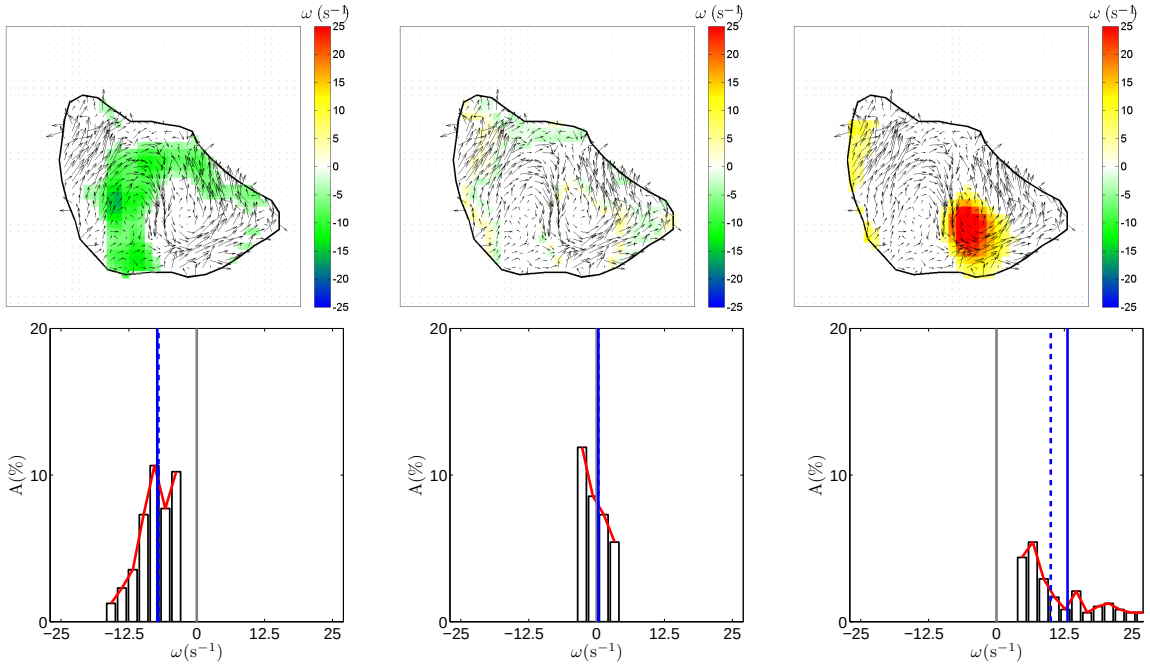
COLOR STREAMLINE PLOT	VECTOR & CONTOUR MAP	HISTOGRAM



Statistical details: t=11, $\begin{bmatrix}\overline{\omega}\\ \sigma\end{bmatrix}_{\mu} = \begin{bmatrix}0.10\\ 9.06\end{bmatrix}\mathrm{s}^{-1}$, $\begin{bmatrix}\overline{\omega}\\ \sigma\end{bmatrix}_{m} = \begin{bmatrix}-1.63\\ 9.23\end{bmatrix}\mathrm{s}^{-1}$

(a) Flow visualisation of right atrium blood motion

COMPONENT 1	COMPONENT 2	COMPONENT 3



$\begin{bmatrix}\overline{\omega}\\ \sigma\end{bmatrix}_{\mu} = \begin{bmatrix}13.09\\ 7.47\end{bmatrix}\mathrm{s}^{-1}$, $\begin{bmatrix}\overline{\omega}\\ \sigma\end{bmatrix}_{m} = \begin{bmatrix}10.00\\ 8.09\end{bmatrix}\mathrm{s}^{-1}$ $\quad$ $\begin{bmatrix}\overline{\omega}\\ \sigma\end{bmatrix}_{\mu} = \begin{bmatrix}0.33\\ 2.00\end{bmatrix}\mathrm{s}^{-1}$, $\begin{bmatrix}\overline{\omega}\\ \sigma\end{bmatrix}_{m} = \begin{bmatrix}0.32\\ 2.00\end{bmatrix}\mathrm{s}^{-1}$ $\quad$ $\begin{bmatrix}\overline{\omega}\\ \sigma\end{bmatrix}_{\mu} = \begin{bmatrix}-7.27\\ 3.04\end{bmatrix}\mathrm{s}^{-1}$, $\begin{bmatrix}\overline{\omega}\\ \sigma\end{bmatrix}_{m} = \begin{bmatrix}-7.04\\ 3.05\end{bmatrix}\mathrm{s}^{-1}$

(b) Segmented flow components and visualisation

Figure 4: **Component analysis of normal right atrium flow.** (a) The visualisation of flow in the right atrium of a normal subject is presented for investigation of the vortex behaviour for time frame t=11 of one cardiac cycle. The statistical properties are based on the chamber flow region. (b) The segmentation of vortical flow using K-means into individual vortices can be performed effectively. We then perform histogram plots of each segmented flow and prepare the statistical properties.

5. DISCUSSION

Flow analysis can be based on the entire flow region and also on individual segregated sub-regions such that each of them comprises of a vortex. A concise analysis of cardiac flow in a heart chamber may be based on the statistical properties of the regional vorticity field.

5.1 Global Flow Analysis

From Figure 4, based on the streamline plots and vorticity contour maps, we are able to observe a counter-clockwise (CCW) vortex in the atrium along with a clockwise (CW) vortex approximately north-west of it. There is an offset of the ω value when median is used as the centroid of the map. Here, two vortices exist in the chamber simultaneously, and because there is a strong CCW vortex versus a weaker CW vortex, $\overline{\omega}_\mu$ and $\overline{\omega}_m$ becomes negative. If the flow is dominantly a clockwise rotation, the shape of the histogram will be adjusted such that its peak will be shifted to the positive ω region, and results in the mean and median being positive.

The magnitudes of σ based on the mean and median are dependent on the characteristic of the flow map. High contrast vorticity image results in a larger standard deviation as compared to low contrast flow images that have vorticity values that do not have a large variance. When there are even number of vortices in the cardiac chamber of analysis, magnitudes of $\overline{\omega}$ based on the mean or median cannot be used with reliability as a mode of comparison as the sum of vorticity values for flow in clockwise directions will cancel those in counter-clockwise directions. Using magnitudes of σ is a more accurate comparison for the intensity of the vortices in the flow map to a limited extent.

5.2 Component Flow Analysis

Breaking down the vorticity analysis into examination of individual vortices allows us to characterize the blood flow behaviour more accurately. Two main vortices are identified: one of clockwise motion with $\overline{\omega}_\mu = -7.27$ s^{-1} and $\overline{\omega}_m = -7.04$ s^{-1}, while the other vortex has $\overline{\omega}_\mu = 13.09$ s^{-1} and $\overline{\omega}_m = 10.00$ s^{-1}. Based on the mean of vorticity distribution, the standard deviation σ_μ of the positive and negative vorticities are 3.04 s^{-1} and 7.47 s^{-1} respectively. Standard deviation σ_m of the positive and negative vorticities are 3.05 s^{-1} and 8.09 s^{-1} respectively. The region of irrotational flow has a low mean of 0.33 s^{-1} and small standard deviation of 2.00 s^{-1}.

If we combined the vortices in the flow, the ensembled averaging of the positive and negative vorticities result in a mean of 0.10 s^{-1} and a large standard deviation of 9.06 s^{-1}. This will not give a correct insight into the actual flow characteristics. Therefore, we can deduce that vorticity segmentation is crucial for an accurate flow analysis of the blood motion behaviour in the heart.

We have discovered that, based on normal conditions, two vortices appear during the initial time frames of the cardiac cycle. However, one dominant vortex exists at the final few time frames. We have not presented the flow results for all the time frames of one cardiac cycle as it is not the aim of this paper to present a discovery on the number of vortices in the right atrial flow. Rather, it is to demonstrate the concept of vorticity flow examination and the analytical framework that has been developed. We have tested the methodology on one case subject and on one time frame as an illustrative example, and further execution of this method on twenty subjects for full cardiac cycle has been carried out although they are not presented here.

6. CONCLUSION

We have applied MR imaging on the right atrium of a healthy subject. The display of information using histograms of vorticity provides an overview of the swirl and strain patterns present within the blood flow. We have also discovered that all the dominant vortices within the atrium of this subject are in the counter-clockwise direction.

The description of vortical flow in the right atrium can be concisely presented using velocity and vorticity flow maps. It is important that the flow is correctly calibrated by referencing Digital Imaging and Communications in Medicine (DICOM) tags in the MR images. Useful visualisation tools such as contour and streamline plots are utilised in our paper. More importantly, we are also able to characterise the strength of the vortices

by compiling histograms of the flow maps and extracting useful statistical properties from them to describe the rotation.

The study has shown that phase contrast MR imaging is a useful and effective way of visualising flow in the heart chambers. Nevertheless, there are other limitations based on this technique, such as longer scan times and availability of the velocity-encoding protocol of the MR scanner. Therefore, MR fluid motion velocimetry has been developed to address these issues. The use of standard MR images without velocity encoding as well as the speed of processing these images to derive the flow information are superior characteristics of the technique.

The construction of a flow grid using more than one set of orthogonal planes can provide a better indication of three dimensional vortex flow structures. Nevertheless, the use of planar flow map slices provides a sufficient representation of the volumetric flow. At the preliminary stage, we can present flow analysis in the two dimensional plane. The use of scans in one plane will be sufficient to reveal flow behaviour for characterisation.

We have developed a vortex segmentation tool for breaking down the flow into its components. This can give a more concise flow analysis of each vortex and it's characteristics. Although it is necessary to input the number of clusters into the unsupervised segmentation algorithm, the analysis will not be affected much by over-segmentation or having too few vortex clusters. In addition, based on our preliminary examinations of the right atrial flow for twenty human subjects, the typical number of dominant vortices ranges from one to two only, and therefore the number of regions that is to be segregated is quite standard for the right atrial flow.

Previous flow analysis are based on qualitative examination of the blood motion without being able to provide any useful and quantifiable data. The developed system described in our paper may be of potential clinical utility for assessing abnormal blood flow, and may be a useful tool for discovering and quantifying flow phenomenon in the heart and arteries.

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