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Enhancement of Intra-Cardiac Flow-Field Data Using Adaptive Kernel Filtering

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Abatract—*A method of determining the optimal kernel size for filtering noise in vortex dominated flow-fields, as found in the cardiac chambers, is presented in this paper. Using synthetic flowfields, generated using harmonic functions and perturbed using Gaussian noises of different amplitudes and spreads, the effect of kernel size on noise removal using the Median filter is tested systematically. It is shown that there exists an optimal kernel size at which the Median filter works best. The size of the optimal kernel is shown to be related to the vortex size. When applied to MRI generated cardiac flow-fields, the approach is seen to reveal underlying vortex patterns thereby aiding as an effective tool in the diagnosis and prognosis of cardiac diseases based on vortices as clinical biomarkers. Signal-to-noise ratio and contrast-to-noise ratio are used to confirm that the optimal size of the kernel is related to the cardiac vortex size, in a manner similar to that observed in studies with synthetic flowfields. Comparison of vortices derived by filtering using fixed kernels and optimally selected kernels, clearly demonstrates the utility of this approach.*

Index Terms: *Median filter, Synthetic vortex, Intra-cardiac flow-field, MRI phase data, Adaptive kernel size, Noise removal, Outlier removal*

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Vortices in the cardiac chambers, as shown in Fig.1, can provide valuable information about the condition of the heart [1]. Pathological hearts are characterized by malformed and maladaptive vortices. Vortices become progressively incoherent in left ventricular remodeling which progresses into stiffening of the left ventricle leading to dilated cardiomyopathy [2]. Life span of cardiac vortices, i.e. fraction of the duration of the cardiac cycle for which the vortex is existing, serves as a biomarker for borderline mPAP and pulmonary hypertension [3, 4]. Left ventricular vortex formation time which is inherently a measure of the length to diameter ratio of the ejected fluid column from the left atrium serves as an indicator for dilated cardiomyopathy [5] and also for assessing the severity of left ventricular diastolic dysfunction [6].

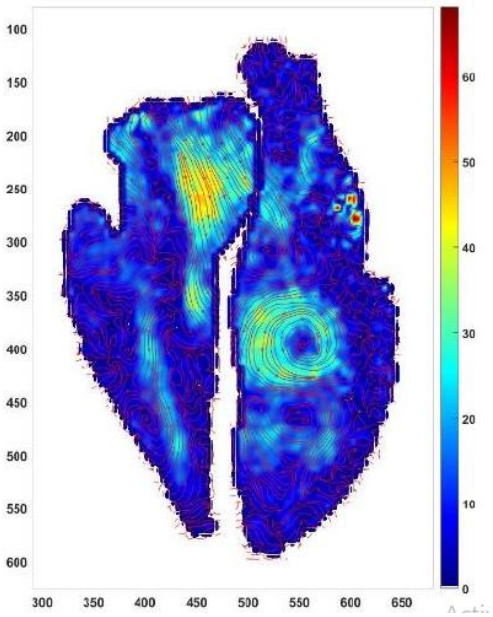

Fig. 1: Unfiltered cardiac flow field

Left atrial vortex size is a biomarker for paroxysmal atrial fibrillation. PAF patients have large left atrial vortex size and it is associated with CHA2DS2-VASc risk score [7]. Left ventricular vortex length and vortex depth serves as a biomarker for left ventricular systolic dysfunction. Patients with abnormal left ventricular systolic function present lower values of left ventricular vortex length and depth values [8]. Sphericity index of left ventricular vortex, which is the ratio of vortex length to vortex width, is lower in left ventricular systolic dysfunction cases [8]. Relative strength of left ventricular vortex which represents the strength of the pulsatile vorticity with respect to the averaged vorticity in the

whole left ventricle is much lower in systolic dysfunction patients than normal persons [8]. Vortical kinetic energy, i.e., the kinetic energy summed up over all the pixels inside a delineated vortex within the left ventricle is a biomarker for heart failure (NYHA, class I-IV). A smaller percentage of diastolic kinetic energy is contained within vortices in heart failure patients compared to healthy controls [9]. The effect on the cardiac flow dynamics of using prosthetic devices like mechanical prosthetic mitral valves can be assessed by the interaction between the coherent structures and the fraction of the time for which they are existing in the diastolic phase [10]. Dynamics of vortical structures from their production, diffusion, dissipation and finally to degeneration provides a good insight into the effect of myocardial wall interactions on the flow. If the frequency of the pulsatile wall interactions is decreased, degeneration of vortical structures occurs [11]. Vorticity which is actually a measure of the rate of rotation when computed in a spatially integrated manner by placing a kernel of a certain size around a point serves as a biomarker for Right Ventricular Diastolic Dysfunction [12] and also for the severity of aortic dilatation[13].

Hemodynamic data, obtained from Phase Contrast MRI (PC MRI) is corrupt with noise arising from various sources. Mismatch between the encoding velocity used and the local peak velocity in the region of interest affects the sensitivity of the acquisition [14, 15]. Too high encoding velocity compared to the local peak velocity leads to very low sensitivity of the encoding device which makes the encoded velocity values cluttered [16] In regions of the cardiovascular system where the flow rate is high, only the component of the noise aligned to the direction of the flow affects the flow data and the noise is correlated to the signal [17]. In regions of low flow rates the noise is totally random and uncorrelated to the signal which makes the noise in those regions more critical to handle [18]. The incidental fluctuations in phase arising from effects other than flow like field inhomogeneity also contribute to noise [19]. Noise arising out of other sources like thermal noise arising from the body [20] or electrical noise [21] from the MRI circuit also makes the data corrupted.

Because of such noises, vortices inside the cardiac chambers can only be seen in particular phases of the cardiac cycle predominantly in the ventricular diastole phase as shown in Fig. 1. In some of the phase, the noise may actually hide vortical structures that are present in the data. Consequently, phase Contrast MRI data requires proper denoising operation to ensure proper visual detection and mathematical operations on the vortical structures present inside the data. The question which arises from here is the optimum kernel size to be used for the filtering operation. This paper will present a method to determine the optimum kernel size based on some synthetic vortex dominated flow fields generated from harmonic sinusoidal functions with added Gaussian noise. The approach will be applied to patient data obtained using MRI imaging. Its ability to reveal cardiac vortices in flow-fields with low signal-to-noise ratios and its utility in improving vortex definitions leading to better quantification of vortex parameters will be presented. A preliminary test case is shown in Fig. 2 where the data in Fig. 1 has been filtered with a median filtered whose kernel size is adaptively determined.

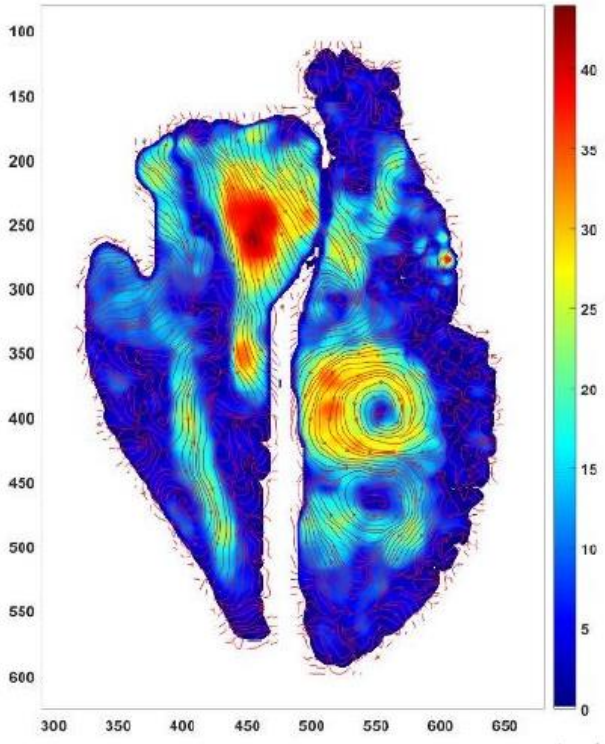

Fig. 2: Cardiac flow field filtered using best kernel size

REFERENCES

[1] Arvidsson, P.M., Kovacs, S.J., Toger, J., Borgquist, R., Heiberg, E., Carlsson, M. and Arheden, H., 2016. Vortex ring behavior provides the epigenetic blueprint for the human heart. *Scientific reports*, *6*(1), pp.1-9.

[2] Pedrizzetti, G., La Canna, G., Alfieri, O. and Tonti, G., 2014. The vortex—an early predictor of cardiovascular outcome?. *Nature Reviews Cardiology*, *11*(9), pp.545- 553.

[3] Reiter, G., Reiter, U., Kovacs, G., Kainz, B., Schmidt, K., Maier, R., Olschewski, H. and Rienmueller, R., 2008. Magnetic resonance–derived 3-dimensional blood flow patterns in the main pulmonary artery as a marker of pulmonary hypertension and a measure of elevated mean pulmonary arterial pressure. *Circulation: Cardiovascular Imaging*, *1*(1), pp.23-30.

[4] Reiter, G., Reiter, U., Kovacs, G., Olschewski, H. and Fuchsjager, M., 2015. Blood flow vortices along the main pulmonary artery measured with MR imaging for diagnosis of pulmonary hypertension. *Radiology*, *275*(1), pp.71-79.

[5] [5] Gharib, M., Rambod, E., Kheradvar, A., Sahn, D.J. and Dabiri, J.O., 2006. Optimal vortex formation as an index of cardiac health. *Proceedings of the National Academy of Sciences*, *103*(16), pp.6305-6308.

[6] Kheradvar, A., Assadi, R., Falahatpisheh, A. and Sengupta, P.P., 2012. Assessment of transmitral vortex formation in patients with diastolic dysfunction. *Journal of the American Society of Echocardiography*, *25*(2), pp.220-227.

[7] Garcia, J., Sheitt, H., Bristow, M.S., Lydell, C., Howarth, A.G., Heydari, B., Prato, F.S., Drangova, M., Thornhill, R.E., Nery, P. and Wilton, S.B., 2020. Left atrial vortex size and velocity distributions by 4D flow MRI in patients with paroxysmal atrial fibrillation: Associations with age and CHA2DS2-VASc risk score. *Journal of Magnetic Resonance Imaging*, *51*(3), pp.871-884.

[8] Hong, G.R., Pedrizzetti, G., Tonti, G., Li, P., Wei, Z., Kim, J.K., Baweja, A., Liu, S., Chung, N., Houle, H. and Narula, J., 2008. Characterization and quantification of vortex flow in the human left ventricle by contrast echocardiography using vector particle image velocimetry. *JACC: Cardiovascular Imaging*, *1*(6), pp.705-717.

[9] Kanski, M., Arvidsson, P.M., Toger, J., Borgquist, R., Heiberg, E., Carlsson, M. and Arheden, H., 2015. Left ventricular fluid kinetic energy time curves in heart failure from cardiovascular magnetic resonance 4D flow data. *Journal of Cardiovascular Magnetic Resonance*, *17*(1), pp.1-10.

[10] Querzoli, G., Fortini, S. and Cenedese, A., 2010. Effect of the prosthetic mitral valve on vortex dynamics and turbulence of the left ventricular flow. *Physics of fluids*, *22*(4), p.041901.

[11] [11] Domenichini, F., Querzoli, G., Cenedese, A. and Pedrizzetti, G., 2007. Combined experimental and numerical analysis of the flow structure into the left ventricle. *Journal of biomechanics*, *40*(9), pp.1988-1994.

[12] Browning, J.R., Hertzberg, J.R., Schroeder, J.D. and Fenster, B.E., 2017. 4D flow assessment of vorticity in right ventricular diastolic dysfunction. *Bioengineering*, *4*(2), p.30.

[13] von Spiczak, J., Crelier, G., Giese, D., Kozerke, S., Maintz, D. and Bunck, A.C., 2015. Quantitative analysis of vortical blood flow in the thoracic aorta using 4D phase contrast MRI. *PloS one*, *10*(9), p.e0139025.

[14] Edelstein, W.A., Bottomley, P.A. and Pfeifer, L.M., 1984. A signal-to-noise calibration procedure for NMR imaging systems. *Medical Physics*, *11*(2), pp.180-185.

[15] Song, S.M., Napel, S., Glover, G.H. and Pelc, N.J., 1993. Noise reduction in three-dimensional phase-contrast MR velocity measurementsl. *Journal of Magnetic Resonance Imaging*, *3*(4), pp.587-596.

[16] Dumoulin, C.L., Souza, S.P., Darrow, R.D., Pelc, N.J., Adams, W.J. and Ash, S.A., 1991. Simultaneous acquisition of phase-contrast angiograms and stationarytissue images with Hadamard encoding of flow-induced phase shifts. *Journal of Magnetic Resonance Imaging*, *1*(4), pp.399-404.

[17] Wolf, R.L., Ehman, R.L., Riederer, S.J. and Rossman, P.J., 1993. Analysis of systematic and random error in MR volumetric flow measurements. *Magnetic resonance in medicine*, *30*(1), pp.82-91.

[18] Conturo, T.E. and Smith, G.D., 1990. Signal-to-noise in phase angle reconstruction: dynamic range extension using phase reference offsets. *Magnetic Resonance in Medicine*, *15*(3), pp.420-437.

[19] Andersen, A.H. and Kirsch, J.E., 1996. Analysis of noise in phase contrast MR imaging. *Medical Physics*, *23*(6), pp.857-869.

[20] Irarrazaval, P., Firoozabadi, A.D., Uribe, S., Tejos, C. and Sing-Long, C., 2019. Noise estimation for the velocity in MRI phase-contrast. *Magnetic Resonance Imaging*, *63*, pp.250-257.

[21] Wymer, D.T., Patel, K.P., Burke III, W.F. and Bhatia, V.K., 2020. Phase-contrast MRI: physics, techniques, and clinical applications. *Radiographics*, *40*(1), pp.122-140.