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Blood Flow Maps Enhanced with Wavelet Analysis

Mejoramiento de Mapas de Flujo Sanguíneo con Analisis Wavelet

Alfredo O. Rodríguez González
Departamento de Ingeniería Eléctrica
Universidad Autónoma Metropolitana
Av. Sn. Rafael Atlixco 186, México, D.F. 09340, México
E-mail: arog@xanum.uam.mx

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Abstract

The imaging modality of magnetic resonance denominated Echo-Planar Imaging is the only real-time technique at since its signal-to-noise ratio (SNR) is poor. To overcome this limitation the continuous transform of the Daubechies wavelet is applied to blood flow maps to improve the image quality. Wavelet coefficients of velocity maps of the cardiac chambers and the descending aorta were calculated. These maps were previously obtained by Half Fourier Echo-Planar Imaging (HF-EPI). Wavelet coefficient images and contour maps are shown. MATLAB programmes were expressly implemented to calculate all the Daubechies wavelet coefficients. The enhanced flow images are compared with previous velocity maps.

Keywords: Daubechies, Wavelet, Enhancement. Magnetic Resonance Imaging, Echo-Planar Imaging, Half Fourier, Flow, Filtering.

Resumen

La modalidad imagenológica denominada Imagenología Eco Planar es la única técnica capaz de generar imágenes en tiempo real hasta el momento. Sin embargo, las imágenes carecen de una buena calidad debido al pobre cociente señal a ruido. Con objeto de mejorar la calidad de la imagen aplicamos la transformada continua de Daubechies a nuestros mapas de flujo sanguíneo. Se calcularon los coeficientes wavelet de los mapas de velocidad de las cámaras cardiacas y la aorta descendente. Los mapas de flujo sanguíneo se adquirieron previamente con la técnica Imagenología Eco Planar combinada con un método parcial de Fourier. Se presentan imágenes y mapas de contorno formados con los coeficientes wavelet. Se desarrollaron programas en lenguaje MATLAB para calcular todos los coeficientes wavelet de Daubechies. Las imágenes originales se compararon con las imágenes obtenidas de la transformada wavelet de Daubechies.

Palabras clave: Daubechies, Wavelet, Mejoramiento, Imagenología por Resonancia Magnética, Imagenología Eco Planar, Método Parcial de Fourier, Flujo, Filtrado.

1 Introduction

Image characteristics such as Signal–to–Noise Ratio (SNR) can be greatly improved, by filtering out those details of no interest and keeping only the relevant information. In a similar fashion, we can apply a filtering process to show the information in more suitable manner in the image. There are many kids of filtering methods used in different type of images generated by X-ray machines, CT scanners, ultrasound methods, etc (Aldroubi y Unser, 1996).

Further, a method to enhance X-ray images might not certainly be well suited to enhance MRI flow images, for example. Usually, the enhancement techniques are applied to remove blurring and distortions, to smooth out the noise in an image, to improve the contrast and SNR (Bankman, 2000).

1.1 Enhancement of EPI Velocity Maps

Flow encoded Echo-Planar Imaging (EPI) is capable of producing flow images of the heart in real-time (Rodriguez et al., 1996, 1997), but these image slow a poor image SNR (Doyle y Mansfiel, 1986; Mansfield y Morris, 1982). Because of this flow and anatomical information is partly masked making difficult interpretation of the heart anatomy, as well as visualisation of blood flow in arteries and the cardiac chambers.

To improve the resolution of our flow maps, so a better SNR can be obtained without loss of spatital resolution and with minimal sacrifice of motion effects. Fourier filtering has been applied to flow encoded EPI images (Half Fourier EPI, Full Fourier EPI) in the past and its results published elsewhere (Mansfiel, 1987, Rodriguez et al., 1997). This method appears to be natural choice due to its ease of computational implementation.

Despite the advantages of the Fourier analysis, it is still not well adapted to the local analysis of a function. Local perturbations of the function may significantly affect all coefficients. It is preferable to have and effective local analysis in our case, such as the one wavelet analysis is able to offer.

1.2 Wavelet Analysis

A relatively new technique and analogous to Fourier analysis which is able to do this local analysis is the so-called wavelet analysis (Daubechies, 1992). Wavelets can be thought as localised waves, which are not oscillating endlessly, but they drop to zero. This relatively new analytical tool can split our image data into components at all scales, and then we can study each constituent with a resolution equated to its scale. Therefore, the wavelet transform performs an analysis in both space and scale simultaneously. Wavelts can produce a natural multiresolution of every image, including the all-important edges: blur is represented by the low frequency part of the Fourier transform.

We applied the Mexican Hat wavelet (second derivative of the Gaussian probability density function: $\exp(-x^2/2)$) to our HF-EPI velocity maps, as a first attempt to investigate in wavelet analysis is capable of improving the image SNR of them (Rodriguez et al., 1998).

1.3 Mexican Hat Wavelet

We used this crude wavelet because it has an explicit expression, accepts the continuous transform and it is symmetric, but it has no scaling function and the analysis is not orthogonal. This wavelet provided us with 14 (this numbrer corresponds to the number of flow maps filtered) good SNR images. There is no need to use the resynthesis process to improve the image quality as in the Fourier case. Cardiac motion can be described in an adequate manner with all the coefficient images. Therefore, this particular wavelet transform proved to be a solid tool to enhance images with poor quality.

Afterwards, we compared our images filtered with the Mexican hat wavelet against the Fourier and windowed transforms and reported our results elsewhere (Rodriguez et al., 1998). These two Fourier methods can only generate one image with a very good SNR, compared to the original velocity maps. The remaining images seem to have just moise. It is necessary to resynthesis the images to get a better image quality.

Yet. The selection of the right wavelet depends on the application (Aldroubi y Unser, 1996). There seems to be no results in the literature suggesting any wavelet in particular to enhanced magnetic resonance images. As mentioned adove, we used the Mexican hat as a filtering–process, although we are pretty much interested to investigate whether there is any other wavelet able to serve as a SNR improvement to our velocity maps.

1.4 Daubechies Wavelet Transform

Our next step, it is to use a smoother function such as Daubechies wavelet transforms (Daubechies, 1992) to find out it this type of wavelets can better the image SNR as well. We would like to investigate if we could extract relevant flow information from our velocity maps with a compactly supported wavelet. It can also be used together with the continuous wavelet transform. Thus, the scaling funcion and wavelet (corresponding to a finite impulse respose (FIR) give good localization in the time domain, because of its compactly supported property.

We preted to produce an SNR improvement of our flow maps generated with Half–Fourier EPI (Rodriguez et al., 2000), using the Daubechies wavelet combined with the continuous wavelet transform. The promising results given by the filtering process based on the Mexican Hat wavelet (Rodriguez et al., 1998) have motivated this work.

However, we have also applied other wavelets such as biorthogonal (Rodriguez et al., 1999), Symlets (Rodriguez et al., 1999–June), Coiflets (Rodriguez et al., 2000–Febraury), 2D Daubechies (Rodriguez et al., 2000–April) and Hilbert transform (Rodriguez et al., 2000–july) with very promising results.

We can express the Daubechies wavelet as follows (Deubechies, 1992): let $P_N(C)$ be sum of the *first* N terms, a polynomial of degree 4N–2:

$$P_N=\sum_{K=0}^{N-1}\binom{2N-1}{K}\left(C^{4N-2(1+K)}\right)\left(1-C^2\right)^K\geq 0 \quad [1]$$

Now, if there is a polynomial P(z) such that

$$|P(z)|^2=P_N(C) \text{ then } |P(-z)|^2$$

is automatically the sum of the *last* N *terms* in the equation adove and the orthonormality condition:

$$|P(z)|^2+|P(-z)|^2=1 \quad [2]$$

$$z=e^{(-2i\pi\omega)},\ P(1)=1 \quad [3]$$

can be satisfied. It is possible to factorise Eq. 1 as:

$$P_N=C^{4N}W_N(s)=\left|\frac{1+z}{2}\right|^{2N}W_N(s) \quad [4]$$

Where

$$W_N=\sum_{K=0}^{N-1}\binom{2N-1}{K}\left(1-S^2\right)^{N-(1+K)}S^{2K}\geq 0 \quad [5]$$

And $W_N(0)=1$.

In order to obtain a filter P (*z*) of the form:

$$P(z)=\left(\frac{1+z}{2}\right)\sum_{n=0}^{N-1} w_n z^n \qquad [6]$$

in only remains to find a square root W (*z*) of $W_N(S)$, ie.

$$W(z)=\sum_{n=0}^{N-1} w_n z^n \qquad [7]$$

satisfying

$$|W(z)|^2=W_N(s) \quad \text{with } W(1)=1.$$

Fig. 1 shows plots of computing the minimal-support, minimal phase Daubechies scaling functions.

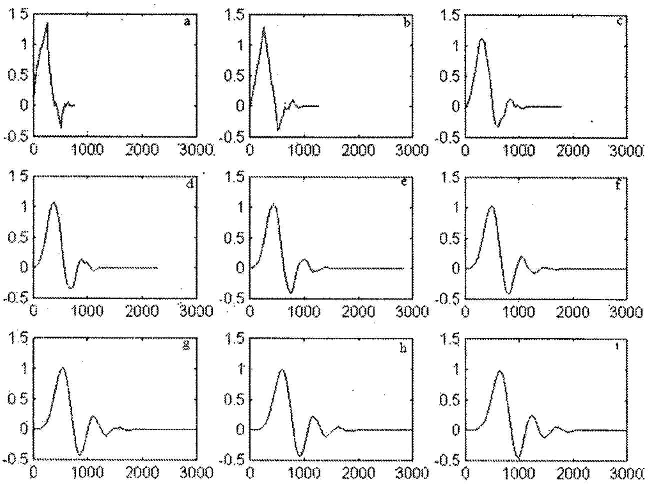

Fig. 1 Plots of the scaling function for Daubechies wavelets with different scales: a) 2, b)3, c) 4, d)5, e) 6, f) 7, g) 8, h)9, i) 10

2 Method

Our enhancement method is based on a method proposed by Doyle and Mansfiel in 1986, in which movie images of the heart acquired within one cardiac cycle. In this paper, the SNR is diminished rather than resolution, thereafter, the SNR is exceedingly enhanced with a Fourier-filtering process, without reducing spatial resolution or foregoing real motion affects, when the object motion is periodic.

In our case, we will replace Fourier-filtering process for a wavelet-filtering method. In particular, we will use the Daubechies wavelet combined with the continuous wavelet transform.

We can consider number of frames (flow maps) fron a sequence of flow measurements acquired within one single cardiac cycle. This is shown in Figure 1.

A velocity vector can be formed with entries $v_i = (P_0, P_1, \ldots P_{M=1})$, i=1, ...|6384 (image size). Then, we applied the Daubechies wavelet continuous transform to V_i, to generate the corresponding wavelet coefficients. This scheme is repeated until covering the entire flow maps, therefore, all velocities are wavelet transformed.

MATLAB™(V.6, The MathWorks Inc., Natick, MA) programmes were specially written to compute all the coefficients of 14 cardiac flow maps, taken at every 50 ms in one single cardiac cycle (Rodriguez et al., 2000–April).

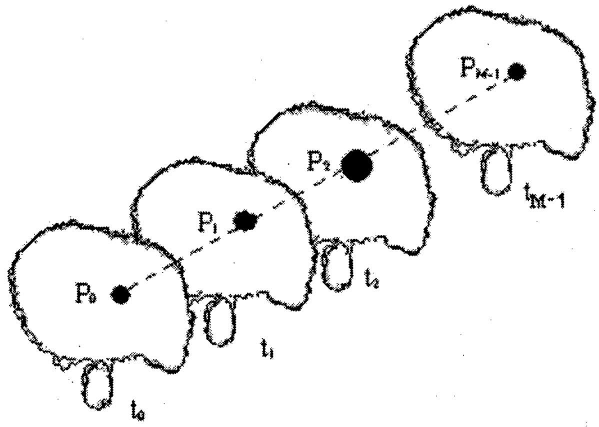

Figure 2. Blood flow maps of the heart: variation of pixel amplitude represented by the dot size. The dot size also shows the velocity change throughout the cardiac cycle

3 Results

For simplicity, we only used one wavelet scale and one polynomial order. We selected both the scaling factor and the polynomial order, *n* (Eq.7), by trial and error until good quality images were achieved. Afterward, we formed images with the wavelet coefficients. The corresponding number of coefficient images were computed with *n*=8 and a scaling factor equal to 40: $C_{14,40}$ (0ms), $C_{2,40}$ (50 ms), $C_{3,40}$ (100ms) ... $C_{14,40}$ (650 ms). Coefficient images are illustrated in Figure 2.

From our coefficient images in Fig. 2, we cn not appreciate any variation of the pixel intensity from one image to the other: all images seem to show the same type of information. Because of that, we calculated the corresponding contour maps to investigate any pattern or trend, see Fig. 3. We have also compared original velocity maps versus velocity maps filtered with the Daubechies wavelet and they are depicted in Fig. 4.

4 Conclusion

4.1 Scaling Factor and Polynomial Order

The potential and efficiency of our method heavily depends on the correct election of these two factors. However, in this case, they were chosen by simple inspection.

Coefficient images wee estimated until we could observe a good image quality. This preliminary approach should be replaced by a solid method based on an analysis of the wavelet mathematical properties. Therefore, its is necessary to investigate into these properties, if we want to take advantage of this mathematical microscope.

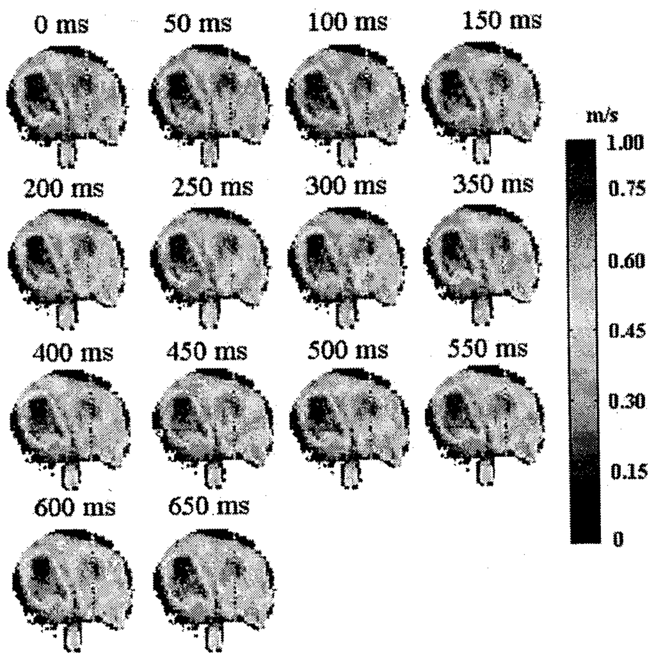

Figure 3. Images formed with the computed wavelet coefficients with the biorthogonal wavelet

4.2 SNR Improvement

The flow map SNR can be significantly enhanced with the Daubechies wavelet with one single scale (Fig. 4). All coefficient images have a very good SNR (fig. 2), then it is not necessary to use the resynthesis process as in the Fourier case. However, it still remains the task of using more than one scale interval to produce good quality flow images. Besides, the relevant anatomical information is now revealed so we could particularly certain regions of the heart.

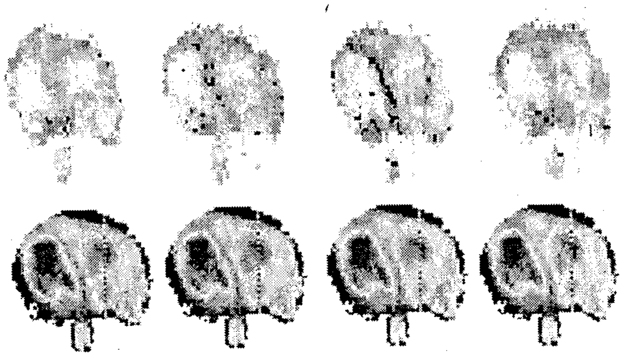

Figure 4. Contour maps of the heart and descending aorta obtained from the wavelet coefficient images. Hemodynamic patters can be eadily observed in the cardiac chambers and descending aorta too.

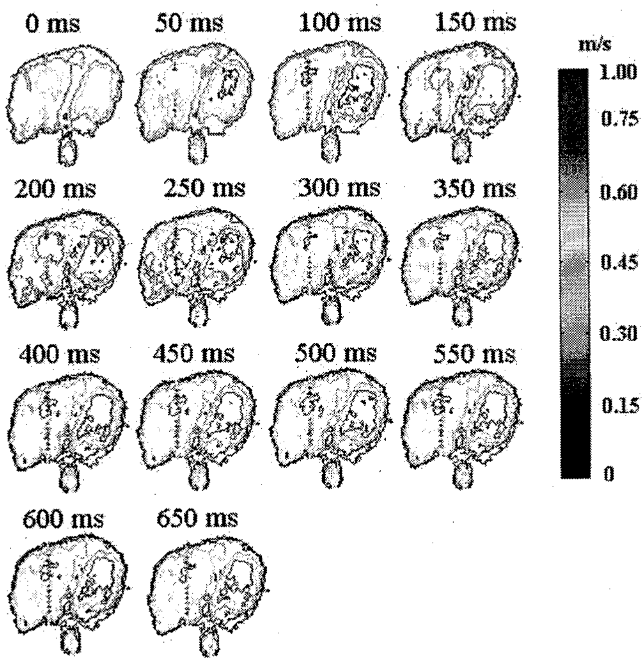

Figure 5. Here, velocity maps are compared: first row, original flow maps and second row, flow maps enhanced with a wavelet–filteing process based on the biorthogonal wavelet. In second row we can observed images greatly enhnanced by the biothogonal wavelet function

4.3 Blood Flow Visualization

By simple inspection, this wavelet can produce detailed velocity contour maps (Fig. 3). Daubechies wavelet is able to present flow information in such a fashion, that we could distinguish flow patters that might characterise blood flow in the cardiac chambers.

In order to be able to recognise these particular hemodynamic patterns, we may apply fractal analysis to our velocity maps. It is also important investigate on which values of n and scale values can facilitate flow visualisation, so more interesting flow information can be extracted from our flow maps.

We can say that Dauvechies wavelet can also improve the flow image quality and produce well–defined contour maps from our velocity maps. Further investigation has to be done to find out if a compactly supported wavelet, such as Daubechies´one is a better analytical tool than the Mexican Hat wavelet for enhancement and flow visualisation purposes.

The combination of Hal–Fourier Echo–Planar Imaging (no invasive and real–time imaging technique) and the continuous transform of Daubechies wavelet (powerful analytical tool), can produce a very robust method not just hemodynamics as well.

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Alfredo O. Rodríguez González, received the B.S. degree in physical engineering from Universidad Autónoma Metropolitana-Atzcapotzalco 1990, México, D. F., México, and the Ph.D. degree in physics (Magnetic Resonance Imaging and Spectroscopy: MRIS) in 1997 from The University of Nottingham, Nottingham, Britain. He is a Titular Professor/Researcher in the Departmento de Ingeniería Eléctrica at Universidad Autónoma Metropolitana-Iztapalapa, México, D. F. His scientific interest include development of RF coils for MRIS, simulation of magnetic and electric fields of RF coils, development of flow MR imaging sequences, wavelet analysis applied to MRIS to model human heamodynamics. He is particularly interested in addressing the problem associated with the enhancement quality of Echo-Planar Imaging.