Wavelets and Heart Sounds

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ABSTRACT: Simple quantitative procedures for analysing heart sounds have been investigated. They are based on the discrete wavelet transform, DWT, particularly those developed within the past decade or so. The early indications are that these transforms are particularly useful in being able to identify clearly the presence of murmur and of some low frequency phenomena associated with abnormal heart sounds. While the origin of the first is well understood, the source of the latter requires further investigation. It occurs at frequencies well below the audio-frequency range and would not be detected with normal auscultatory procedures. The work is continuing.

1. INTRODUCTION

While the ear is adept at perceiving patterns in non-stationary acoustic signals such as those produced by the heart, it lacks the ability to respond to frequencies in the infrasonic region and to quantify signals in the audio-frequency range. Short-time Fourier transforms (STFT) have been shown to be useful for presenting visual and quantitative images of heart sounds [1-3], and can easily identify certain abnormalities. They are limited however in their ability to resolve low frequency components although they are excellent in highlighting higher frequency phenomena such as murmur.

The development of the discrete wavelet transform (DWT) over the past couple of decades [4], has introduced a method for analysing sounds from a different perspective. In addition, they have a constant percentage type of character (unlike the constant bandwidth approach of the STFT), which opens up the possibility of examining low frequency phenomena in more detail than is possible with the STFT. There are tradeoffs of course at the high frequency end and time will tell if, on balance, they provide more insight than do STFTs for identifying a wide range of abnormal heart sounds. The early stages of the study reported here suggest that DWTs do indeed have potential and there is no difficulty in identifying abnormal sounds. The diagnostic importance of the significant amount of infra-sound associated with abnormal hearts has yet to be established.

2. HEART SOUNDS

The functioning of the heart and the origin of heart sounds is only briefly discussed here and is available in much more detail elsewhere [5].

Heart sounds are of two essential types. The first is of a transient nature and is of short duration. It is associated with the commencement and cessation of blood flow as the result of opening and closing of various valves – the familiar "water hammer" effect. The second type can be more continuous and is associated with turbulent flow which gives rise to murmurs.

In a normal cardiac cycle the transient heart sounds occur twice – "lubb-dupp". The first sound is associated with vibrations in the atrio-ventricular chambers and the contained blood. They are caused by the abrupt rise in ventricular pressure resulting from ventricular contraction. That is immediately followed by a release in pressure at the onset of the ejection of blood through the semi-lunar valves. The vibrations of the ventricles and blood are transmitted through the surrounding tissues and reach the chest wall where they can be detected.

The second heart sound occurs when the semi-lunar valves close, usually fairly suddenly, causing a rapid cessation in blood flow. The resulting vibrations of the blood and vessels similarly transmit through to the chest wall. This sound is usually of a slightly higher frequency than the first and is, of course, of shorter duration.

Murmurs are caused, as noted earlier, by turbulent flow. This could be the result of imperfect closure of valves, restrictions to the flow paths, pathologic communications in the cardio-vascular system or ruptured intracardiac structures. They are usually of significance although "innocent" murmurs sometimes occur in younger children.

Clearly the transmission path from the heart to the chest wall will affect the character of the sound detected at the chest. Some researchers advocate invasive procedures to minimise this effect [6], but this study has not followed that approach at this stage æ a simple non-invasive procedure is preferred.

3. DISCRETE WAVELET TRANSFORMS

The discrete wavelet transform is just one of many ways available for decomposing a signal into some more basic components. There are several different families of wavelets, and the ones considered here are relatively recent and are due to Daubechies [7,8]. Other families are still under investigation.

Each family of wavelets consists of its own basic shape characterised by the "mother" wavelet. This is required to have very specific properties as discussed [9]. There are in addition, a whole series of related wavelets, all of the same

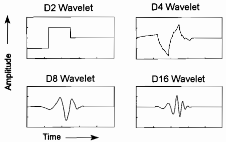

Figure 1. Some typical Daubechies wavelets.

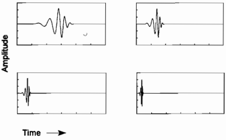

Figure 2. Some members of the D16 wavelet family.

basic shape as the mother wavelet, but translated in time, and contracted by various amounts depending on their respective levels.

An appreciation of some of the different Daubechies wavelets can be obtained by reference to Figure 1. There, four of the wavelets are shown, namely D2, D4, D8 and D16.

They are indicative of this group. It happens also that the D2 wavelet is also referred to as the Haar wavelet due to its earlier development, [10]. Some of the members of the D16 wavelet are shown in Figure 2. They are all of the same general shape, as noted above, but are of shorter and shorter duration. They thus belong to different "levels". Level 0 contains one wavelet which occupies the entire period of the signal under analysis. Level 1 contains two wavelets, level 2 contains four wavelets, level 3 contains eight wavelets, and so on. For a signal containing 512 data points, the highest level, level 8, will contain 256 wavelets, all equally spaced and partly overlapping, as they are for the lower levels.

Each individual wavelet at each level is adjusted in amplitude so that, when they are all summed, the resulting signal will closely represent the original signal.

It is worth noting in passing that since the various wavelets are "compact" in the time domain, they will not be compact in the frequency domain. Not only does this vary with level, it also varies from family to family. Some idea of this latter variation can be obtained by reference to Figure 3. There, the spectral representations of four different wavelets at level 5 are given. Note that the most compact, the D2, has the most extended spectra, while the least compact, the D16, has the most compact spectra, as expected.

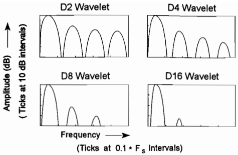

Figure 3. Spectra of some Daubechies wavelets.

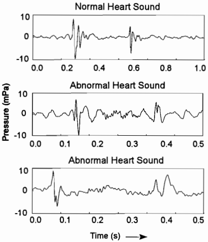

Figure 4. Some heart sounds.

It is not immediately obvious which of the above wavelets is the most helpful when analysing heart sounds and when attempting to identify abnormalities. Clearly for very abrupt changes in level, the D2 series would be likely to be more useful but this series would struggle when representing more gradual changes. The D8 and the D16 families may have some advantage since their general shape and character are more like those of the normal heart sound as discussed later. However, any of the wavelet families can be used legitimately to decompose the heart sounds and each will present its own particular interpretation.

4. APPLICATION OF DISCRETE WAVELET TRANSFORMS TO HEART SOUNDS.

The three heart sounds shown in Figure 4 are representative of a normal heart, and two levels of abnormality. The first was produced by a young adult (20 years) with no known abnormalities. The second came from a child (2 years) who was known to have a ventricular septal defect giving rise to a murmur between the first and second heart sounds. The third belonged to an adult (32 years) who was suffering from hypertension.

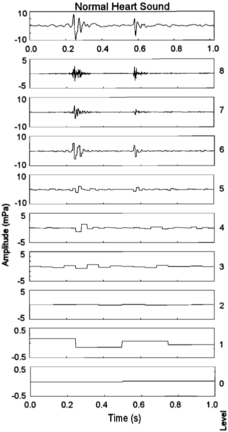

Figure 5. D2 series of a normal heart sound.

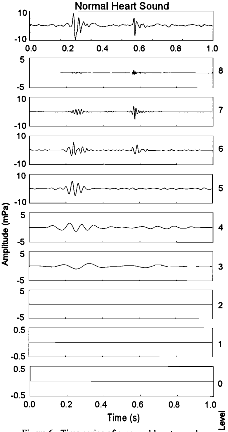

Figure 6. Time series of a normal heart sound.

The signals were collected by a B & K type 4146 microphone and associated power supply each capable of recording very low frequencies. The signals were originally sampled at 1000 Hz but subsequently resampled so that each cardiac cycle consisted of 512 data points.

Signal analysis was carried out using programs from [9] in conjunction with the Matlab and DADiSP suite of programs. Final graphical representation made use of the Wordperfect package Presentations.

4.1 Normal Heart Sounds

The decomposition of the normal heart sound using D2 wavelets is shown in Figure 5. Note that all components exist at all levels although the greatest amplitudes occur at level 6. This decomposition can be considered as a filtering process with the amplitudes at each level depending on the type of filter (D2 in this case) as well as the character of the original signal.

The decomposition using the D16 wavelet is given for comparison in Figure 6. Levels 5 and 6 now have about equal amplitudes and there is less activity at level 8. The amplitudes at the other levels are relatively comparable. Figures 5 and 6 thus represent different and legitimate ways of decomposing the signal.

Space does not permit presentations of all results for all of the wavelet series but the D4 and D8 wavelets did not appear to offer any particular insight which was not already reasonably apparent from these two figures.

The information shown in these figures can be presented more compactly using the method developed in [11]. Thus discrete wavelet "maps" or "scalograms" offer essentially the same information except that the various amplitudes at the various levels are plotted as contours on a decibel scale. The abscissa again is time while the ordinate is wavelet level æ the higher the level, the finer the scale.

Scalograms for the D2, D8 and D16 wavelets are shown in Figures 7(a), 7(b) and 7(c) using contours at 3dB intervals. Each figure clearly shows the first and second heart sounds with the first sound extending over more levels than the second as expected. Each also shows periods of relative calm. There is some low level activity in the time period from 0.6 to 0.8 seconds at levels 3 to 6. The significance of these has not been established.

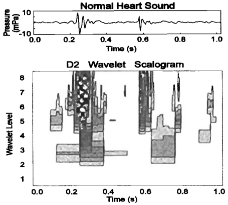

Figure 7(a)

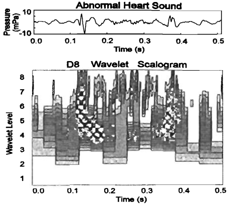

Figure 7(d)

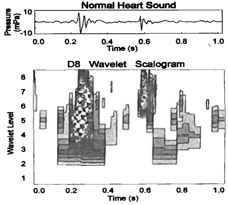

Figure 7(b)

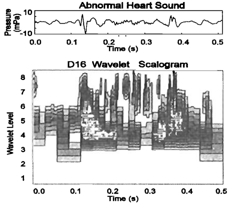

Figure 7(e)

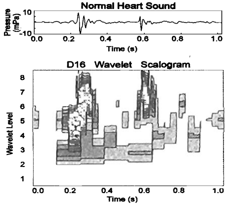

Figure 7(c)

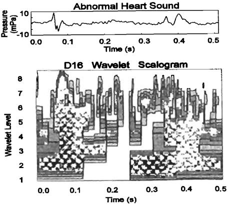

Figure 7(f)

Figure 7. Discrete wavelet transforms of heart sounds.

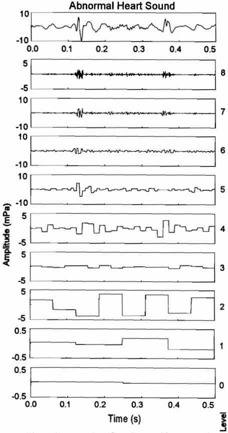

Figure 8. D2 series of an abnormal heart sound.

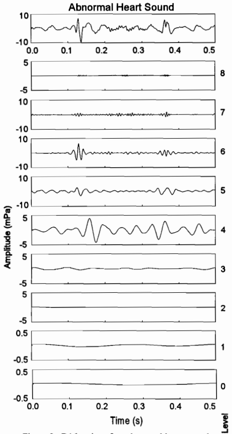

Figure 9. D16 series of an abnormal heart sound.

All of the scalograms give a clear quantitative impression of a normal heart sound and are offered as a basis for comparison with the abnormal heart sounds.

4.2 Abnormal Heart Sounds

The time series decomposition of the first of the abnormal heart sounds of Figure 4 using the D2 wavelet is given in Figure 8. This signal now contains more continuous activity at levels 7 and 8 which can be related to the murmur produced by blood flow through the ventricular septal defect. There is also considerable activity at the lower wavelet levels, eg levels 2 to 4, although the origin of those signals is not known. These components are below the audio-frequency range.

The D16 representation, Figure 9, confirms the changed pattern at level 4 although the level 2 component is comparable to that of the normal heart. The continuous activity at levels 7 and 8 are again apparent and can be distinguished from those of the normal heart sound given in Figure 6.

Scalograms based on the D8 and D16 wavelets are given in Figures 7(d) and 7(e). There are some clear differences in the abnormal heart when compared with those of the normal heart sound, Figures 7(b) and 7(c).

The components due to the murmur are evident at about 0.25 seconds at levels 6 to 8. The continuous activity at level 4 noted

previously is again apparent. There is no doubt that the appearance of these scalograms is considerably different to those for the normal heart. There is no difficulty in identifying abnormal heart sounds.

The final example of a wavelet time decomposition of an abnormal heart sound, that of the third signal given in Figure 4, is shown in Figure 10 using the D16 wavelet. There are distinctive features.

Continuous activity occurs at very low wavelet levels, namely levels 0,1 and 2. These are all well below the audio-frequency range. The sharpness of the second heart sound is missing æ there are now no conspicuous peaks at levels 6 and 7, for example, as there are in say Figure 6. Most activity occurs at level 4. The first heart sound has very little activity at level 6 in contrast to that of the normal heart.

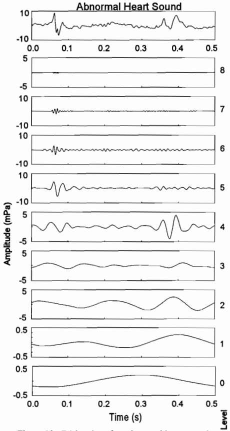

Figure 10. D16 series of an abnormal heart sound.

The corresponding scalogram is given for this heart sound in Figure 7(f), and may be compared with the normal heart sound of Figure 7(c). The most striking differences are highlighted, as expected, at the lower wavelet levels. Thus levels 1,2,3 and 4 are fairly continuous. The first and second sounds are not nearly as distinct and there also appears some evidence of murmur at levels 6 and 7 during a fair proportion of the cardiac cycle. The overall impression is one of disorder in stark contrast to the uncluttered simple pattern of the normal heart sound pattern.

5. CONCLUSIONS

Discrete wavelet transforms are useful for identifying normal and abnormal heart sounds. The use of scalograms in particular presents clear quantitative impressions of the variation in heart sound with time, and also from heart to heart.

Each of the four wavelets investigated was easily able to detect convincingly abnormalities in heart sounds and it is still not clear which will finally prove to be the most useful. Further experience with a wider range of heart sounds is needed.

The discrete wavelet transform is particularly attractive in being able to detect the presence of activity at low wavelet levels, i.e. at very low frequencies. The origin of these components in the abnormal heart sounds is not known. These components would not be detected with conventional auscultatory procedures. At the same time heart murmur is also easily detected with components appearing conspicuously at the higher wavelet levels. Their position in time is clearly distinguishable (unlike the low level components).

There is good reason to explore and to exploit discrete wavelet transforms for analysing heart sounds. They appear to be ideally suited for the purpose.

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