DEVELOPMENT AND COMPARATIVE EVALUATION OF WAVELET-BASED FILTERS FOR ENHANCING X-RAY BONE IMAGES

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Four wavelet-based enhancement filters, hard, soft, twin-threshold and sigmoid enhancement methods [1-3], were developed in C++. Images were transformed by the Discrete Wavelet Transform (DWT) in 3 decomposition levels. The detail coefficients were then processed and the output image was obtained by the Inverse DWT. These four filters were applied to digitized X-ray bone images and the processed images were blind-reviewed by an experienced radiologist (N. Dimitropoulos), in terms of image quality and introduction of artifacts. Wavelet-based soft, hard and twin-threshold enhancement filters showed significant improvement in image quality. The introduction of artifacts was kept minimal in the case of the hard-thresholding after fine adjustment of the filter parameters. The sigmoid filter failed to improve image quality by introducing, in many cases, image artifacts thus rendering the image non-diagnostic. Processing time was less than 3s on a Pentium IV, making all filtering algorithms plausible for clinical application. Wavelet-based image enhancement filters, have been found to improve image quality effectively, without the introduction of artifacts.

1. Introduction

One of the most important issues in radiological image evaluation is the contrast and the details of fine structures. By developing digital radiographic devices, it is possible to deal with contrast improvements and overall image quality enhancement by using specialized image processing algorithms. The current report focuses on X-ray bone image enhancement, using wavelet-based image analysis and processing, already applied in mammographic images [1,2,3]. The results were obtained in relation to image quality improvement and the introduction of artifacts, both evaluated by an expert radiologist for all the resulting images. The results show the positive effects of these algorithms in terms of improving their diagnostic content.

2. Materials and methods

Sets of X-ray bone images were used for this project, received from a device in 1024 X 1024 X 8 bits (30 chest, 15 hands, 10 pelvis, 5 legs). The Discrete Wavelet Transform (DWT) was applied in 3 decomposition scales. The enhanced images were obtained by the inverse DWT. Four wavelet-based image enhancement filters (hard, soft, twin linear and sigmoid thresholding enhancement functions) were developed in C++.

In hard image enhancement method, the thresholding procedure is a piecewise linear mapping function whose main utility is noise suppression. The resulting filter equalizes any of the detail wavelet coefficients of level 3 between –T and +T with zero, while all the other coefficients higher than +T and lower than –T are multiplied by a gain G, which is also a filter parameter. The values for both threshold T and gain G were optimally evaluated by trial-and-error in relation to previous research.

The equations that describe this filtering process can be described as piecewise linear functions [1]:

$$
\begin{aligned}
W_{out} &= W_{in} + T(G-1) && \text{if } W_{in} > +T \\
W_{out} &= W_{in} - T(G-1) && \text{if } W_{in} < -T \\
W_{out} &= 0 && \text{if } -T < W_{in} < +T
\end{aligned}
$$

Figure 1 presents a typical illustration of this composite function.

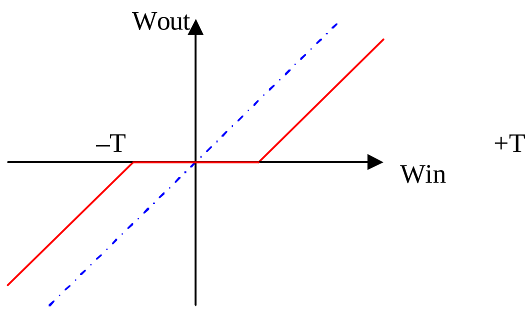

Figure 1: Hard wavelet thresholding enhancement.

In soft image enhancement method, the thresholding procedure is also a piecewise linear mapping function, only now there is a non-zero coefficient adjustment within the thresholding range. The resulting filter multiplies the detail wavelet coefficients of level 3 between +T and –T with the chosen gain G. All the other coefficients are adjusted using a linear function that combines both T and G parameters. In this case, the low-valued detail coefficients, as well as the noise factors, are multiplied with gain G. If the value of G is greater than 1, both high-detail and noise portions of the signal are amplified, possibly degrading the resulting image when noise overpowers the diagnostic features included in high frequencies.

The following equations describe formally the above procedure [2]:

Wout = Win + T(G-1)   if Win > +T
Wout = Win – T(G-1)   if Win < –T
Wout = G*Win   if –T < Win < +T

Figure 2 presents a typical illustration of this composite function.

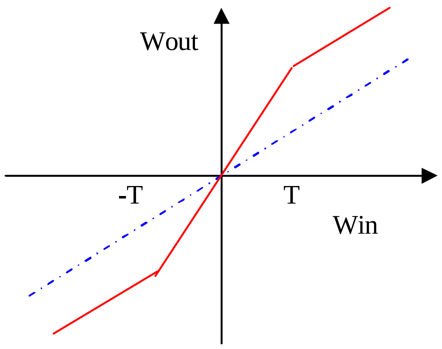

Figure 2: Soft wavelet thresholding enhancement.

In sigmoid image enhancement method, the thresholding procedure is a non-linear function, combining two sigmoid curves for the regions inside and outside the thresholding range, respectively. In this case, the transitions between the two regions are continuous and therefore the wavelet coefficients are adjusted using a much smoother mapping method. The wavelet coefficients of level 3 between –T and +T are decreased in values around zero, while coefficients outside the thresholding range are amplified [1]. As before, the main parameters are gain G and threshold T. The gain value G ranges from 0 to 1 and the threshold value T can be chosen according to the calculated values of detail wavelet coefficients.

The equations that describe this filtering process can be described as a set of combined sigmoid functions:

Wout = a*[sigm (c*(Win-b))–sigm(-c*(Win+b))]

a = 1 / { sigm(c*(1–b))–sigm(-c*(1+b)) }
sigm (y) = 1 / (1+exp(-y))

Figure 3 illustrates schematically the above function:

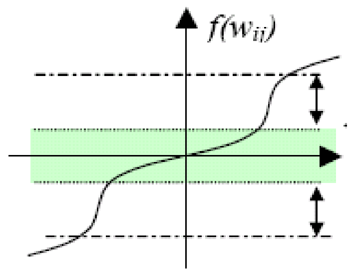

Figure 3: Sigmoid enhancement technique [1]

The two–threshold image enhancement method is a combination of the hard and soft thresholding methods. Implementing two different thresholds T1, T2, and the same gain G, this algorithm can be used to enhance high frequency content while at the same time suppress noise factors, similarly to a high-emphasis spatial filter. Typically, threshold values T1<T2 form a double thresholding region, one inside the other. Detail wavelet coefficients of level 3 inside the inner thresholding region between –T1 and +T1 are set to zero, similar to the standard hard method. For coefficients outside the inner region are adjusted according to a modified soft thresholding method, using T2 as the specified threshold. Therefore, very low coefficients are set to zero, suppressing the noise factors effectively, while at the same time it amplifies high-frequency coefficients for improving image details.

This composite function is defined formally by the following equations [2]:

Wout = Win+(T2*(G–1))–(T1*G)   if Win>T2
Wout = G*(Win–T1)   if T2>=Win>T1
Wout = 0   if –T1<=Win<=T1
Wout = G*(Win+T1)   if –T1>Win>=–T2
Wout = Win–(T2*(G–1))+(T1*G)   if Win>T2

Figure 4 illustrates the twin-threshold technique.

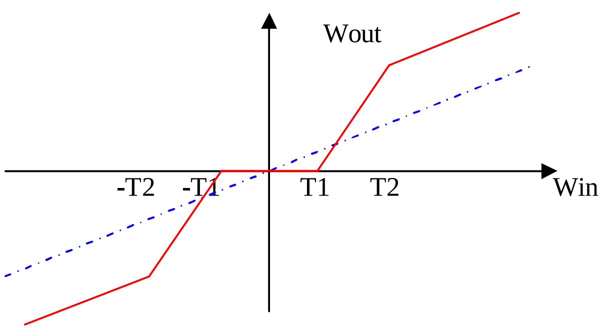

Figure 4: Twin-thresholding wavelet enhancement.

3. Results

The resulting images were compared on the base of overall quality improvement and minimal introduction of artifacts, all evaluated by an expert radiologist. In all cases, the results were acceptable for the three of the four applied methods. The overall best results were achieved by the hard enhancement thresholding method. The soft and twin-threshold techniques also produced similar results in general. The sigmoid method was considered rather unsuitable for X-ray bone images enhancement, as it produced a lot of artifacts related to both noise and edge deformation, even with the best experimentally achieved values for gain and threshold parameters. Specifically, when the gain and threshold values were too high, artifact introduction increased tremendously and it caused image destruction. Optimal parameter values were found between 0,4 and 0,5 for gain and under 20 for threshold. Table 1 demonstrates the optimal values obtained for a tarsus X-ray image.

Table 1: Selected gain and threshold values

	Hard	Soft	Sigmoid	Twin
Threshold1	7	7	0.06	7
Gain	3	3	0.14	2
Threhold2	–	–	–	27

Images in figure 5 illustrate the results of applying each thresholding algorithm.


(a)


(b)


(c)


(d)


(e)

Figure 5: Results of the 4 thresholding methods. Image (a) is the original image. Hard method is applied in image (b), which is the best case. Soft method is applied in image (c). Sigmoid method is applied in image (d). Twin-threshold method is applied in image (e).

4. Discussion

Based on the results of the soft and the twin-thresholding methods, the enhancement effectiveness is similar in both cases, however in the soft thresholding the existing noise is amplified considerably. The obtained image quality was acceptable in both cases. The twin-thresholding algorithm is equally effective in terms of image quality, but without the noise amplification factor. In the case of twin-thresholding, setting the threshold T2 value the same as the one used in the soft thresholding, the image enhancement is identical in both cases. The threshold T1 of the twin-thresholding method is the value that controls the noise suppression, as it functions as a hard-limiter for very small detail wavelet coefficients.

Another important conclusion is the fact that when the initial image resolution was small (300dpi) it was necessary to increase the gain G value in order to achieve optimal results. When the resolution was increased (600dpi) the gain G had to be smaller. The difference for optimal G value in these two cases was roughly 35%. In contrast, the threshold value was independent to the image resolution, according to the evaluation made by the expert radiologist.

The sigmoid filter was concluded as unsuitable for X-ray bone image enhancement, as it produced smoothing or edge-deformation effects, while in some cases it produced artificial structures even for thresholds similar to the other algorithms.

With regard to wavelet decomposition levels, applying the same thresholding parameters levels at level 1 or level 2 resulted in lower image enhancement than when applying them at level 3. Comparing the image enhancement in the first and second scale versus the third scale, for the same threshold T and gain G value, the improvement of fine details was roughly 20% greater according to the expert's evaluation. This is mostly due to the fact that wavelet decomposition scales larger than 2 contain most of the informative content related to the visual quality of underlying tissue structures and other clinical findings. Thus, wavelet enhancement at level 3 is mostly related to clinical aspects of image quality, rather than other technical aspects enhanced at lower decomposition levels.


(a)


(b)


(c)


(d)

Figure 6: Comparative wavelet enhancement of the original image (a) at the first (b), the second (c) and the third (d) decomposition levels.

5. Conclusion

The necessity of image enhancement is the main reason of this project. Four wavelet image enhancing methods, well-suited for mammographic image enhancement, are evaluated comparatively in bone X-ray images. The improvement of image quality was significant, while at the same time kept artifact generation minimal when optimal gain and thresholding parameters were applied.

6. References

[1] R.Mekle, A.Laine, S.Smith, et.al. (2000): 'Evaluation of a multi-scale enhancement protocol for digital mammography', Wavelet Applications in Signal and Image Processing VIII, Proc.SPIE 4119, pp. 1038-1049. (Conference Proceedings)

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