CHAPTER 5

CONCLUSIONS AND FURTHER OUTLOOK

The goal of this study was to establish some of the practical limitations of the REC technique and to evaluate applications where the REC technique would improve the quality of ultrasound imaging. In this final chapter, the conclusions formulated are summarized and future directions and extensions to the work presented are described.

5.1 Characterization of REC

In Chapter 2, the REC technique was characterized and practical limitations were discussed. Specifically, the detrimental effect of nonlinear distortion on the compression of REC echoes was established. The effects consisted of amplification of the harmonics when the Wiener filter operated near inverse filter mode which resulted in high sidelobe levels being produced. The compression performance was improved by pre-filtering the higher harmonics. Pre-filtering the higher harmonics reduced the sidelobe levels significantly.

Moreover, the practical limitations of the REC technique that were encountered during the course of these studies were assessed. Specifically, the effects of frequency-dependent attenuation and pre-enhanced chirp construction limitations were examined. In terms of attenuation, the main effect evaluated was the center frequency shift and bandwidth loss. It was observed in that study that REC suffered from a larger center frequency shift when compared to CP because of its larger bandwidth. Furthermore, the pre-enhanced chirp was evaluated in terms of center frequency amplitude versus peak amplitude. The findings suggest that, when attempting to increase the resolution by a factor of two, a loss in signal-to-noise ratio was obtained when compared to a linear chirp excitation under the voltage limited scenario. Nonetheless, by exciting a source with a pre-enhanced chirp, an increase in signal-to-noise ratio is obtained when compared to conventional pulsing because of the larger time-bandwidth product of the coded signal.

Finally, the possible heating of the source when the source was excited with a pre-enhanced chirp was evaluated. It was observed in the heating study that the pre-enhanced chirp did not produce any significant source heating greater than would be achieved with a similar linear chirp. Therefore, it was concluded that heating of the source was not of greater concern using the REC method.

5.2 Applications for REC

In Chapter 3 various applications where the use of the REC technique improved image quality were evaluated.

The first application evaluated was REC-FC. With REC-FC the contrast of ultrasound B-mode images was improved by reducing the speckle variance. This reduction in variance came from subdividing the bandwidth into subbands to generate partially uncorrelated images that could be compounded to improve the contrast. Because REC had a larger bandwidth when compared to conventional methods, the bandwidth was subdivided into more subbands, which increased the amount of speckle reduction that occurred. A major benefit observed for the REC-FC full width case was that there were no significant losses in axial resolution when compared to conventional imaging schemes; however, an improvement in contrast was obtained. Therefore, it would be interesting to evaluate other speckle reduction schemes for the REC-FC full width case. These speckle reduction schemes include speckle reduction geometric filtering, homomorphic deconvolution, anisotropic diffusion, and wavelet denoising and shrinkage. A complete study would apply the same technique to the REC reference image and the CP reference image.

Similarly, the same techniques could be applied to the eREC-FC image obtained. In eREC-FC, all of the frequency compounded images were summed together to the reference image. The eREC-FC technique improved both resolution and contrast when compared to the REC-FC full-width case.

The REC-FC images appeared to have better boundary definition when compared to CP. A simple edge detection scheme was applied in order to verify this assertion.

However, future studies should examine a method that quantifies the apparent edge enhancement obtained by using REC-FC and eREC-FC. Furthermore, the REC-FC technique on an array imaging system could be combined with spatial compounding to improve contrast even further.

The second application evaluated was REC-QUS. With REC-QUS, REC was used to obtain improved parametric images using estimates of ESD. These improved estimates were obtained because the larger bandwidth resulting from REC meant that more information was contained in the power spectrum representing the scattering function. Therefore, a reduction in variance was obtained. Furthermore, the reduction in variance translated into improved contrast of the parametric images of ESD. In addition to obtaining the ESD, the effective acoustic concentration could be obtained. Further studies should examine the REC-QUS technique for improvements in the estimates of the effective acoustic concentration because the effective acoustic concentration is dependent on the initial estimate of ESD. Adding another parameter could be beneficial in the differentiation of tissues. Furthermore, because the ESD results for REC-QUS had a smaller variance when compared to conventional QUS, the effective acoustic concentration results should improve. Therefore, REC-QUS could have the potential to significantly improve the diagnostic capabilities of ultrasound. In addition to reducing the variance, REC-QUS obtained improved estimates of ESD for a smaller axial pixel size. Angular compounding studies demonstrated that improved estimates of ESD can be obtained for a smaller lateral pixel length. Therefore, by combining REC-QUS with angular compounding, the estimates of ESD could be further improved and smaller pixels sizes, both laterally and axially, could be used in parametric imaging.

The significance of smaller pixel sizes could be an increased ability to detect and diagnose smaller lesions. The work involving REC-QUS in this study only utilized phantoms in both simulations and experiments. Studies of REC-QUS where the ability to differentiate between different kinds of tumors should be evaluated in future studies.

Finally, a study where the analysis bandwidth was partitioned into smaller bands so that the power spectrum could be evaluated using different frequency scales would be interesting. Scatterer sensitivity to particular frequencies varies with scatterer size. Therefore, by splitting the spectrum into different scales, several images could be generated that might be sensitive to different scales of scatterers as if the interrogated tissue was being imaged by multiple sources.

5.3 Spatially Varying Weiner Filter

In Chapter 4, the detrimental effect that the spatially varying impulse response had on the compression of REC echoes was examined and quantified. Furthermore, several schemes were devised and assessed to mitigate the spatially varying effect in the compression scheme. Specifically, schemes that partially corrected for the diffraction, frequency-dependent scattering, and both diffraction and frequency-dependent scattering locally were evaluated. Improved results in terms of sidelobe reduction were obtained, but only when the targets were isolated (i.e., no speckle content surrounded the target). When the target was isolated echoes from the targets were used as references to self-compress the echoes and improve the compression performance. However, when speckle was present, the improvements were nearly nonexistent because it was hard to ascertain the frequency-dependent scattering function of the object.

A different spatially varying Wiener filter that compensated for the $\overline{eSNR}$ locally was devised. The spatially varying filter created a signal strength map to improve the compression performance. The spatially varying Wiener filter improved image contrast and improved the $eSNR$ in deeper regions of the object imaged. The tradeoff was a slight degradation in resolution and a slight increase in sidelobe levels in order to improve the eSNR and image quality as a function of depth.