Variable Compressions with RF and Baseband Processing for Dynamic Range Expansion of Elastograms*

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Abstract

Expanding the dynamic range in elastography is important since the stiffness dynamic range encountered in the pathological breast is on the order of 40-60 dB, while a single compression elastogram is limited to a dynamic range of only 15-20 dB. It has recently been shown that using variable applied compressions significantly improves the dynamic range of hard regions. However, some softer regions in the elastogram may remain noisy. A technique that selects high signal-to-noise ratio (SNR_e) strain data obtained by a careful combination of processing both baseband and bandpass signals was shown to estimate soft tissue strains more accurately. In this paper we combine the two techniques along with averaging of the available strain data to obtain a composite elastogram that displays the entire dynamic range of strains in tissue. This way we can achieve both a signal-to-noise ratio and a dynamic range improvement, two main measures of image quality in elastography at a given resolution. Results of this method are shown on 2-D simulations.

Key Words

Baseband, Dynamic range, Elastography, RF, Strain

1. Introduction

Elastography is a method that uses ultrasonic signals before and after tissue compression in order to estimate the strain induced in the tissue using cross-correlation techniques [1]. In elastography we are mainly interested in generating a strain image, called 'elastogram', which is closest to the actual strain image of the tissue scanned. The actual strain image of the tissue depends on the stiffness distribution of the various elements found in the tissue and on the internal and external boundary conditions involved.

From recent biomechanical measurements [2-3] it appears that the stiffness dynamic range in the cancerous breast can reach up to 60 dB. In order to use elastography as a diagnostic tool in the area of breast cancer, it is important to recover and display the full tissue strain dynamic range in one elastogram. Elastographic dynamic range expansion is important for two main reasons. Firstly, some common lesions such as fibroadenomas (benign) and scirrhous carcinomas (malignant) have comparable acoustic and elastic properties [3]. If the dynamic range is large enough in this particular range of strains, elastography will be able to differentiate between such lesions. Secondly, the recovery of very high strains that are primarily a result of high mechanical stress concentration artifacts are essential for the accurate reconstruction of the elastic modulus distribution [4]. In addition, it can also be shown

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*Supported in part by NIH grants RO 1-CA 60520 and PO 1-CA 64579.
(Received Nov 26, 1996; Accepted in final form Feb 3, 1997)

that, due to these mechanical artifacts, the resulting strain dynamic range can be higher than the stiffness dynamic range.

The elastographic dynamic range can be defined as the width of the Strain Filter at an arbitray SNR_e level. This was shown to have a practical *upper limit* of 15–20 dB [5]. Therefore, with the current practice of elastography, a 40 dB strain dynamic range is not recoverable in a single compression elastogram. There are two complementary methods for recovering the information lost: the variable applied strain approach [6, 13] and the combination of baseband (envelope) and bandpass (RF) signals [7]. The former assures the recovery of lower strains (harder tissue elements) where the tissue strain incurred with a single compression is not sufficient. The latter uses the baseband information to recover the higher strains (of softer tissue elements or mechanical artifacts) that are distorted by decorrelation noise when using the RF. In other words, the RF cross-correlation method for strain estimation provides *better* information while the baseband provides less information that is *more robust* [7, 9–11]. We note here that this method is significantly different from methods that use baseband (envelope) correlation for a coarse detection of the peak and RF correlation for a more precise detection [9–11]. In the case of the method described in this paper we use the baseband to *estimate the strain* when the RF data have decorrelated [7]. In other words, we are not combining RF and baseband for strain estimation but use each method independently from the other according to the magnitude of tissue strain to be estimated [7].

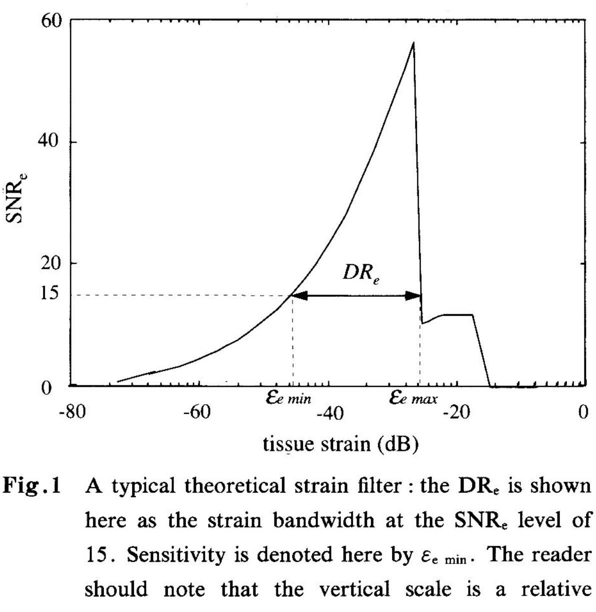

Fig. 1 A typical theoretical strain filter: the DR_e is shown here as the strain bandwidth at the SNR_e level of 15. Sensitivity is denoted here by $\varepsilon_{e\,min}$. The reader should note that the vertical scale is a relative scale. This also holds for all subsequent figures.

In the following section we describe the predicted theoretical improvement in the dynamic range using strain filtering analysis.

2. THEORY

The Strain Filter is a tool that can quantitatively show the *upper bound* of the elastographic performance [5]. It plots the elastographic signal-to-noise ratio (SNR_e) versus the tissue strain. It is determined by the mechanical, ultrasonic and signal processing parameters of the system. An example of a typical Strain Filter is plotted in Fig. 1. On the low strain (left) side, the strain filter is limited by random noise in the system, and on the high (right) strain side it is bounded by decorrelation noise. Therefore, the width of the strain filter indicates the strain dynamic range measured with elastography.

The dynamic range of elastography can be defined as the width measured either from the bottom or the top of the strain filter. However, due to the spiky shape of the strain filter (Fig. 1), it would not be recommended to measure the width from the top. Instead, we define the elastographic dynamic range (DR_e) as the width of the Strain Filter at an arbitrary SNR_e level, i.e.,

$$DR_e \mid_{SNR_e=15} = 20 \log_{10} \frac{\varepsilon_{emax}}{\varepsilon_{emin}} \qquad (1)$$

From the typical case shown in Fig. 1 it is obvious that the DR_e, as defined, is on the order of 20 dB.

Hence, the Strain Filter shows the range of strains that can be displayed in the elastogram.

For different compressions, however, different tissue elements will experience the strains that fall within the Strain Filter. The method of variable applied strains [6] is based on the idea of appropriately combining data from different compressions in order to cover the entire strain dynamic range in the tissue (Fig.2). These data are selected according to the value of the SNR_e. By appropriately scaling these values depending on the known amounts of applied strain they correspond to, we can form a composite elastogram containing all the strain values with the highest obtainable SNR_e [6]. Therefore, this method results in a better visualization of lower strains and can help the differentiation among hard lesions of comparable stiffnesses. Note that the method described in [6] can only be used to expand the dynamic range on the left side of the strain filter, towards the small strain areas. This is because the initial compression used in this method sets the limits to the largest strains (incurred in the softest regions) that can be estimated by the composite elastogram. The subsequent (larger) compressions may cause the RF signal to decorrelate in these regions and the strain estimated could be noisier. An example of such a case will be shown later.

Another issue that arises now is how to expand the dynamic range on the right side of the strain filter;that is, recover the decorrelated data due to high strains. The variable applied strain method is basically limited by the first compression. However, the first compression can be reduced in order to accurately estimate strains in softer areas but the exact initial compression required is a function of the tissue size and unkown tissue stiffness. For this study we assume that the scan has already been collected and that the softest areas have already partially decorrelated *a priori*. They then have to be recovered *a posteriori*. This is actually true in practice, when the properties of the tissue scanned are unknown and, therefore, it is impossible to know what the smallest compression should be.

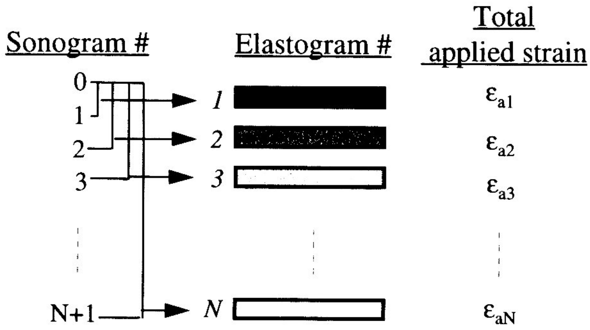

Fig.2 Example of using N variable applied strain compressions (indicated by the color variation).

If at the first compression some of the tissue areas experience strain that leads to a significant decorrelation of the RF signal, these areas will be displayed as noisy regions on the elastogram. The baseband information of the signal can then be used in these areas and decorrelation will occur at higher strains since envelope decorrelation is much slower than the RF one [7]. This is also depicted on the strain filter (Fig.3). Fig.3 shows that a careful combination of the bandpass and baseband signals might be used to obtain the widest possible dynamic range for one compression. This is because the baseband strain filter can offer an additional dynamic range expansion on

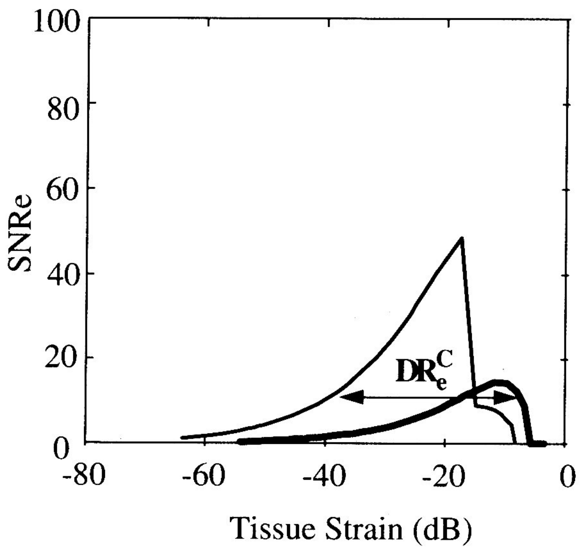

Fig.3 Baseband (solid bold) and RF (solid) strain filters. Note the supplementary dynamic range DR_e^C ($>DR_e$) on the high strain side achieved by the baseband strain filter (0 dB=100%).

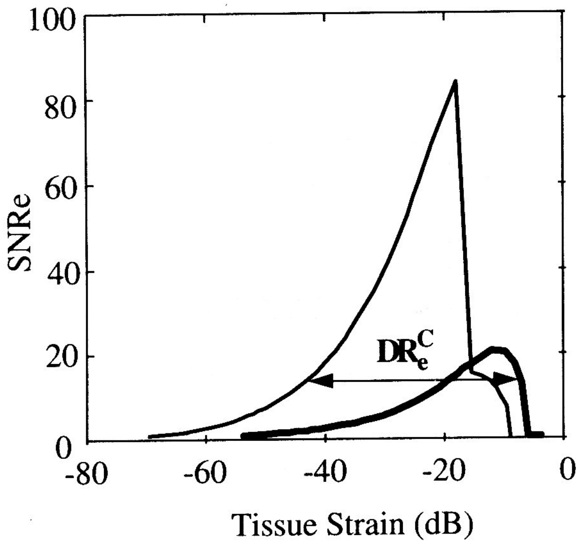

Fig.4 Example of averaging four RF and baseband elastograms resulting in an increase in height of the baseband (solid bold) and RF (solid) strain filters (improved SNR_e). Note that the DR_e^C remains the same (0 dB=100% strain).

the order of 6 dB on the right side of the strain filter.

Figure 3 shows that the baseband estimated data have lower SNR_e values than the RF estimated data [7]. Added averaging (Fig.4) has been shown to increase the SNR_e, i.e., increase the height of the strain filter [8]. Konofagou et al. [6] have also shown that averaging of the variable applied strain data is more beneficial in measuring strains in softer regions, since these strain estimates are more numerous being selected at smaller compressions. Since the baseband method is also applicable for higher strains (incurred at softer regions), added averaging leads to a significant increase of the SNR_e for the baseband estimated strains. This meas that averaging raises the height of the baseband strain filter (Fig. 4). For the aforementioned reasons, averaging was used in the results to follow.

To summarize, the combination of these two dynamic range expansion methods is able to improve the elastographic image quality. In the following section the algorithm used to process the signals as well as the simulations used to corroborate the theory is described.

3. METHODS

The principle of the dynamic range expansion method is to optimally select strain data corresponding to each individual compression along with averaging to reduce random fluctuations. We list below the steps followed in the algorithm. At each step we denote by DR_e^C the total (or composite) dynamic range at the $SNR_e=15$.

1. N compressions with an incremental strain of ε_a are applied corresponding to N+1 sonograms (Fig.2).
2. N-q elastograms are computed corresponding to each q^{th} compression ($1 \leq q \leq N-1$) of applied strain $q^*\varepsilon_a$ using both RF and baseband signals.
3. The RF and baseband elastograms (Fig. 3) that correspond to the same amount of incremental applied strain are averaged (Fig.4). For example, if there are M elastograms corresponding to the same incremental strain of $q^*\varepsilon_a$, these elastograms are averaged in order to reduce the variance by $\sqrt{M}$(or, equivalently, increase the SNR_e by $\sqrt{M}$), assuming that the data are uncorrelated. Comparison of Figs.3 and 4 shows the effect of averaging three elastograms on the RF and baseband strain filters.
4. For each amount of applied strain we compute the SNR_e values of both averaged baseband and RF strain estimates and then store those strain values with the highest SNR_e. Since it is theoretically predicted that the baseband approach would perform better than the RF only for higher strains [7], the baseband analysis is sped up by considering only the strains higher than 1.5%. This threshold was set based on theoretical results [5]. From Fig.5 the reader should note that the baseband method is mainly needed for the first com-

pression data, assuming that there is enough overlap between the variable applied strains.

5. We compare the SNR_e values of the strain estimates calculated for the same pixel with different compressions and choose the strain estimate with the highest SNR_e. The SNR_e, as defined by the Strain Filter equation, depends on the sonographic signal-to-noise ratio, the correlation coefficient and the estimated strain value, when the rest of the system parameters are fixed. When the decorrelation noise is low (high ρ), the sonographic noise determines the SNR_e value. The opposite is true when the decorrelation noise increases. For more details the reader should refer to [5,6].

The selected strain estimate is scaled appropriately (or shifted in the logarithmic strain domain) according to the corresponding amount of applied strain. For the q^{th} elastogram we multiply the corresponding estimates by $\frac{N}{q}(1 \leq q \leq N-1)$ and so on. This is equivalent to shifting the strain filter, which the selected strain value corresponds to, by $20 \log_{10}\left(\frac{N}{q}\right)$(Fig.5).

Finally, all these values are assembled into the composite elastogram that corresponds to a (hypothetical) applied strain of $N^*\varepsilon_a$. As a result, the composite elastogram contains a range of strains (DR_e^C), which is possibly larger by orders of magnitude than when using a single compression (DR_e), i.e., $DR_e^C >> DR_e$(Fig.5).

The method was tested on a 2D simulated phantom with triangular finite elements assuming a plane-strain model. For more details the reader is referred to [6]. The total stiffness dynamic range was 40 dB with three inclusions of identical size and at 10, 20 and 40 dB harder than the embedding homogeneous background (20 kPa).

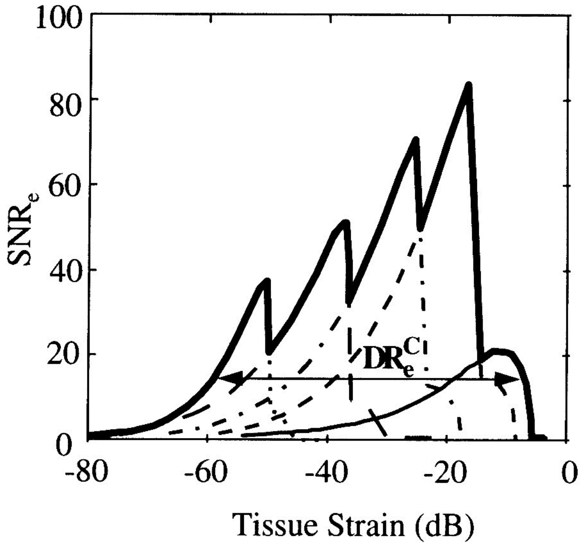

Fig.5 The variable applied strain method combines strains corresponding to different compressions. In order to assemble the data we *scale* it appropriately (see text for details) and this translates into *shifting* the corresponding strain filter in the log domain. Here is an example of four different compressions with a series of variable applied strains with a 6 dB incremental strain. The combination of the data corresponding to these strain filters gives the composite strain filter (solid bold) with a DR_e^C larger than DR_e by orders of magnitude.

The center frequency was fixed at 5 MHz with a 60% fractional bandwidth and a sonographic SNR of 40 dB. Crosscorrelation processing was performed with 3 mm windows and 1.5 mm overlap between consecutive windows. The sampling frequency was 63 MHz. Finally, we used a total of eight compressions of the same incremental strain of 0.25% ($N=8$, $\varepsilon_a=0.25\%$).

4. RESULTS

Figures 6 and 7 show the results obtained with single compressions and at different steps of the dynamic range expansion method, respectively. They are also shown in color to allow a high display dynamic range. In addition, the gray scale was fixed to a scale ranging from 0 to 40 dB so as to facilitate meaningful comparison between images of different dynamic ranges.

Figure 6 (a) shows the ideal strain image of the

40 dB stiffness dynamic range phantom at an applied strain of 2%. The reader should note the stress-concentration artifact induced by the boundary conditions, which is situated between two inclusions, the one closest to the top and the one closest to the bottom of the phantom. This artifactually soft region rises approximately 2.4 dB from the background stiffness value. It is important to recover this artifact in case we want to use the elastogram as the input to the inverse problem method in order to reconstruct the elasticity distribution image [4]. In Figs. 6(b) and 6(c) we show the single compression elastograms with 0.75% and 2% applied compression, respectively. Neither of the two can display the entire dynamic range of 40 dB because their dynamic range is limited to 20 dB. In the first case (Fig.6 (b)), although all three inclusions are visible, their differentiation based on strain values is impossible. In the second case (Fig.6(c)), the inclusions experience strains that are within the range of the strain filter. Therefore, they can be easily differentiated. However, the background has significantly decorrelated. In addition, the aforementioned mechanical artifact in either case is not properly recovered (because the baseband method was not applied); instead, it appears noisy.

In Fig.7(a) the ideal case for 40 dB at an applied strain of 2% is also shown here in order to facilitate comparison. Figure 7(b) is the composite elastogram resulting from using the variable applied strain method (algorithm step 5, skipping 3 and 4); that is, expanding the dynamic range only on the low strain side. The two hardest inclusions can now be better differentiated from each other and from the background. As expected, the high strain artifact remains noisy, but is better recovered than with the single compression (Figs.6(b) and (c)), since in this case the smallest compression used was 0.25% (i.e. $<$ 1%), thereby avoiding the highly decorrelated data. Fig.7(c) shows the results of added averaging (algorithm step 3 and 5 skipping 4). As expected, the variance of the estimates decreases and, as a result, the SNR_e increases. Therefore, the resulting elastogram appears smoother. Finally, Fig.7(d) shows the result obtained by incorporating the baseband approach (i.e., including algorithm step 4) into Fig.7(c). The mechanical artifact has now been recovered thanks to the slower decorrelation of the baseband data. The SNR_e of the final elastogram has also increased due to the selection process of variable applied strain method and the added averaging. The reader should note the similarity between Figs.7 (a) (ideal) and 7(d) (composite elastogram), demonstrating that the original dynamic range has been essentially recovered.

5. DISCUSSION

Single compression elastography is limited to a dynamic range of 15–20 dB. Some tissues, however, can have a stiffness dynamic range of up to

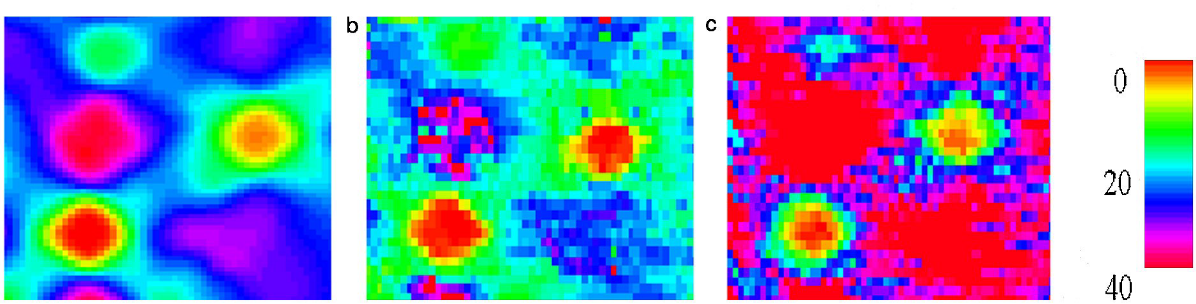

Fig.6 a) Ideal strain image for DR_e=40 dB and b) Elastogram of a single compression at 0.75% applied strain, c) Elastogram of a single compression at 2% applied strain.

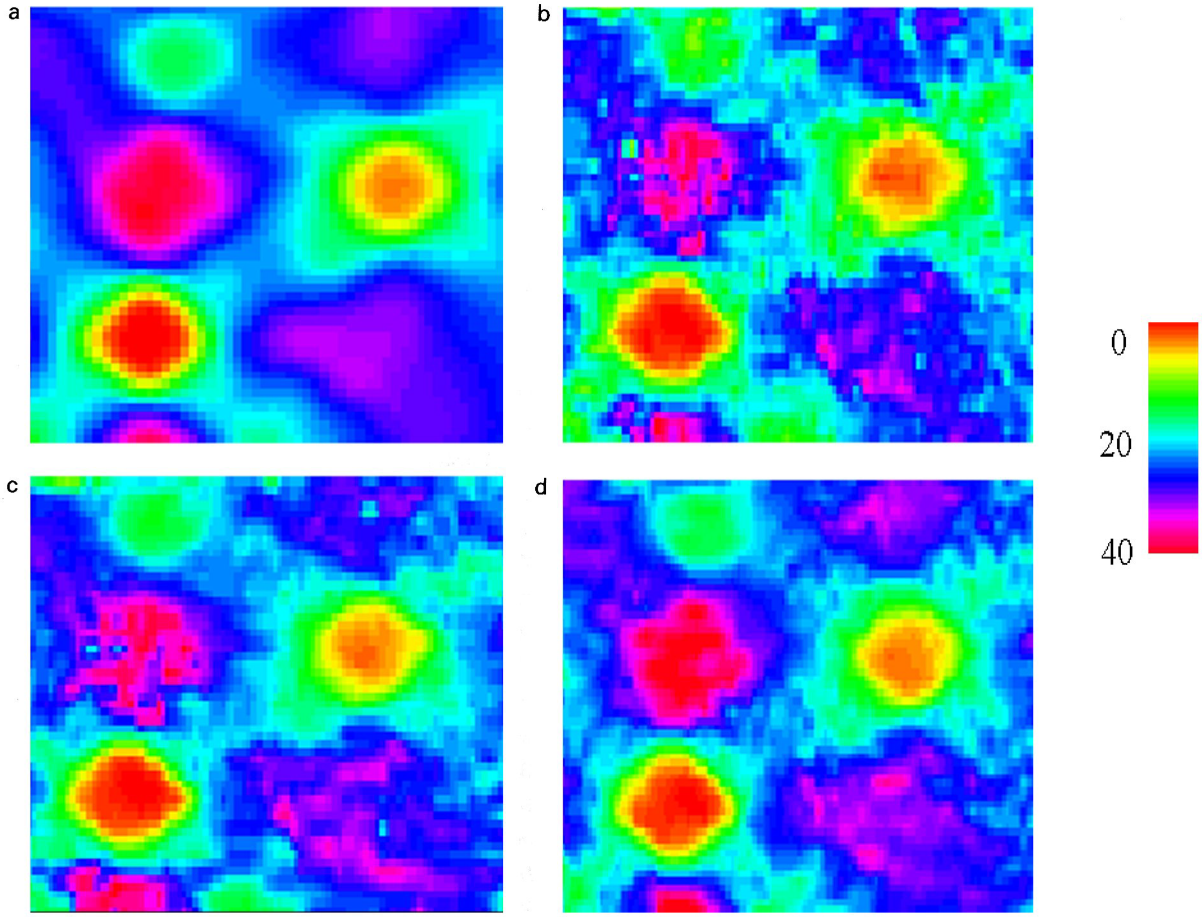

Fig.7 a) Ideal strain image for $DR_e = 40$ dB and b) Composite elastogram resulting from the variable applied strain method, c) case b) with added averaging and d) case c) with also additional baseband processing.

60 dB. It may, therefore, be required to recover the high *and* low strains that are noisy in the single compression case. Recovering the noisy low strains is very important in the sense that hard inclusions of comparable stiffnesses can be more easily differentiated and, thus, their benign or malignant state more accurately assessed. For example, the fibroadenomas (benign) and scirrhous carcinomas (malignant) with a stiffness difference of 10–15 dB [3] should now be easily viewed and differentiated on the composite elastogram. Recovering the noisy high strains is essential in the case where the elastogram is used as the input to an elasticity reconstruction algorithm.

In terms of the strain filter, this translates into increasing its width (and thereby the dynamic range) on both its low-and high-strain ends. The variable applied strain method [6] achieves the former, and the baseband method [7] achieves the latter. The combination of both shows that it is possible to increase the elastographic dynamic range by orders of magnitude (Fig. 7(d)). This becomes very significant when dealing with already collected data and when the dynamic range has to be recovered *a posteriori*. Another equally important aspect of this method is that the dynamic range can be recovered regardless of the elastic properites of the tissue scanned. The quality of a single compression elastogram, however, depends critically on the tissue as well as the amount of compression used.

The use of the variable applied strain method also led to the increase in the SNR_e, since only the highest SNR_e strain estimates are used to assemble the final elastogram. In addition, the added averaging contributed to a further SNR_e improvement. So, the overall combination of all these methods achieves the improvement in both dynamic range and signal-to-noise ratio without affecting resolution or other system parameters. This is assuming that the resolution is defined proportional to the window size T [11], which in the case of this method has not been modified.

It appears that as long as we can compress the tissue with higher applied strains, it is possible to recover all the low strain areas as long as there is no tissue distortion. In other words, the expansion of the dynamic range on the left (low strain) side of the strain filter is limited by the effects of tissue distorion due to large compressions. The same is not, however, valid in the case of the baseband approach, since it is limited to a modest dynamic range expansion of 6 dB [6]. If some tissues or artifacts have strains outside the strain filter or if the first (smallest) compression in the variable applied strain series is too large, these areas will appear noisy and the total dynamic range will not be recovered. Both DR_e and SNR_e can also be improved by using adaptive stretching [12]. This last approach is expected to significantly expand the dynamic range on the high side of the strain filter.

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