The medical use of ultrasound has expanded enormously over the last two decades, due largely to the fact that it is safe, allows real-time visualization of moving structures, is suitable for many clinical applications, and is relatively inexpensive.

However, like all imaging modalities, ultrasound is still subject to a number of inherent artifacts that compromise image quality and impair diagnostic utility. For example, there are various sources of ‘noise’ within ultrasound images. Perhaps the most important is ‘speckle’, which arises from coherent wave interference [1] and gives a granular appearance to an otherwise homogeneous region of tissue. Speckle reduces image contrast and detail resolution, and makes it difficult to identify abnormal tissue patterns (or texture) that may indicate disease. Another source of noise is ‘clutter’, which arises from beamforming artifacts, reverberations, and other acoustic phenomena. Clutter consists of spurious echoes which can often be seen within structures of low echogenicity, such as a cyst, or within amniotic fluid, and which may be confused with ‘real’ targets. Finally, another potential source of noise, especially in deep-lying regions, is thermal noise arising in the electronics of the transducer or beamformer. All these sources of noise affect the ability of the radiologist or sonographer to recognize tissue anomalies by interfering with what is, essentially, a pattern recognition process in the observer’s brain. Figure 1a and b shows how the addition of random noise, similar in characteristics to ultrasound noise, affects the ability to recognize real objects in an ordinary photographic image. Hence, reducing noise should improve effective pattern recognition and diagnosis.
Recent approaches to artifact reduction in ultrasound

Some recent developments in ultrasound signal acquisition and beamforming have begun to address many of the limitations discussed above. For example, imaging using harmonics generated through non-linear propagation in tissue (e.g. Tissue Harmonic Imaging™ from Philips) has dramatically reduced noise from clutter and other acoustic artifacts. Real-time spatial compounding (SonoCT™), in which echoes are acquired from multiple directions and later combined, has dramatically reduced speckle, clutter and thermal noise, while also enhancing the visualization of specular reflectors [2, 3].

Role of image processing

Image processing has had some role to play in improving image quality and reducing artifacts, such as noise reduction from averaging image in time (persistence), simple algorithms for enhancing edges, and adjustments to gray levels to boost contrast resolution (gray maps). Nevertheless, its benefits have been somewhat limited compared with what has been achieved in other imaging modalities such as CT and MRI. There are several impediments to the use of image processing in ultrasound. These include:

- the complexity of ultrasound images, especially the large variety of image characteristics, both diagnostic and artifactual
- user resistance to a ‘processed’ appearance and fears that information may be lost or diagnostic criteria may change
- the computational power needed for real-time (20–60 frames/s) image rates, in order to deal with the wide range of clinical applications.

As an example of reasons why the first two points are so important, Figure 1c and d shows the effect of applying a classical edge enhancement algorithm and a smoothing algorithm, respectively, on the noise-induced fruit bowl image. The edge enhancement algorithm is effective at enhancing edges, but it also has a tendency to boost noise. Although the smoothing algorithm is quite successful at reducing the noise level, it also blurs edges and suppresses true texture and structure. Other conventional imaging-processing algorithms present their own image quality trade-offs. For example, persistence can be quite effective in reducing noise (including speckle) but, since it relies on averaging images over time, any significant movement of the target or transducer will lead to blurring of real targets.

Adaptive image-processing algorithms

To be effective, especially for ultrasound, an image-processing algorithm has to be able to recognize the difference between real targets and artifacts, and to modify its processing accordingly. Such an algorithm is known as an ‘adaptive’ algorithm – it adapts automatically to the nature of the target, ideally both locally (i.e. within an individual image) and temporally (over time from image to image), reducing artifacts while preserving diagnostic information. Various examples of adaptive ultrasound image processing algorithms have been explored in the scientific literature.

Bamber et al. [4] developed a speckle reduction algorithm that changed the amount of smoothing depending on the local statistics of the image (the ratio of local variance to local mean), utilizing the fact that speckle has characteristic statistical properties and can thus be identified by its gray-level distribution. Where speckle is identified, the smoothing is increased; in other non-speckle regions the smoothing is reduced or eliminated, thus preserving detail. Although preliminary clinical evaluations on static images were encouraging, the processing time of six seconds per frame made it unsuitable for real-time evaluation. A real-time version was implemented on dedicated hardware [5], but limitations in the analog portion of the hardware led to degraded resolution and the addition of artifacts.

Loupas et al. [6] developed a similar algorithm based on the statistical properties of gray levels, but instead of explicitly identifying speckle the algorithm used a generalized noise model to identify regions in which local variation of the gray level distribution was consistent with noise (these were smoothed) or structure (little or no smoothing). A real-time version implemented on dedicated all-digital hardware demonstrated impressive speckle reduction while preserving most structural details.

Stetson et al. [7] developed an adaptive gray-scale mapping algorithm for improving tissue contrast, although the real-time version was not continuously...
(i.e. temporally) adaptive since the gray-level transforms were pre-set using static images of similar targets. There are versions of related gray-level optimization algorithms on commercial ultrasound systems that similarly pre-set the transforms using static images, typically acquired when the user hits an ‘optimize’ button.

**Principles of XRES adaptive image enhancement**

The impressive results achieved by research in adaptive ultrasound image enhancement algorithms strongly suggested that the time had come for the application of these techniques to commercial systems. In searching for appropriate solutions, Philips Ultrasound came upon several adaptive algorithms that had been developed by Philips Research for other imaging modalities. One of these, now known as XRES®, had many of the characteristics thought necessary for successful application to ultrasound – it was truly adaptive to the components of the image itself, it allowed for a significant amount of artifact reduction and target enhancement, and it was efficient enough for real-time implementation on a high-speed general-purpose processor.

Like some previous adaptive ultrasound algorithms, XRES involves both an analysis phase (in which artifacts and targets are identified) and an enhancement phase (in which artifacts are suppressed and targets enhanced), the enhancement phase being controlled by the results of the analysis phase. However, unlike previous adaptive image processing algorithms developed for ultrasound, the analysis phase of XRES takes into account more than one characteristic of the target, such as local statistical properties, and textural and structural properties. The textural and structural information in particular is vital for identifying the strength and orientation of interfaces and thus allowing directional filtering of these targets in the enhancement phase. For example, smoothing is applied along an interface to improve continuity, while edge enhancement is applied in the perpendicular direction. In regions identified by the analysis phase as being homogeneous (no structure or texture), smoothing is applied equally in all directions. Thus XRES is designed to both suppress noise (from speckle, clutter or thermal sources) as in previous algorithms, and to enhance interfaces and margins. In this sense the visual impact of XRES on ultrasound is quite similar to the impact of SonoCT – i.e. an improvement in nearly all characteristics of the image.

Figure 2a and b shows an example of XRES applied to an ultrasound image of a normal liver, while Figure 2c and d shows the results of applying conventional (i.e. non-adaptive) edge enhancement (Figure 2c) and smoothing (Figure 2d) algorithms. The non-adaptive algorithms achieve some improvements in edge definition or speckle/noise reduction, but at the expense of speckle enhancement in the first case and loss of resolution (especially edges) in the second. Conversely, XRES achieves simultaneous improvements in both edge enhancement and speckle/noise reduction.

In addition, XRES is a multi-resolution algorithm. This means that all processing – analysis and enhancement – occurs at multiple scales within the image. This is achieved by the generation of spatial frequency sub-bands, created from down-sampled images, which represent the different scales to be analyzed and enhanced respectively. The XRES enhanced image is the result of combining all enhanced sub-bands. This improves robustness by allowing the XRES algorithm to adapt itself to variations in artifacts and feature scale, as well as to the variable size of anatomical structures. It is somewhat similar to a human observer looking at an image from different distances to perceive relevant features at different scales.

As noted previously, the visual impact of XRES on ultrasound images can be quite similar to that of SonoCT. The question therefore arises of whether XRES reduces the need for SonoCT, or vice-versa? In fact, neither is the case. SonoCT and XRES achieve similar results by two very different means, resulting in complementary and indeed additive improvements. By acquiring ultrasound data from a number of viewing angles, SonoCT adds new tissue information to the compounded image, thus reducing the relative visibility of artifactual information (Figure 3a and b). XRES, on the other hand, reduces information associated with artifacts directly, while leaving the true tissue information largely unaffected (Figure 3c). The result is that the combination of SonoCT and XRES (Figure 3d) achieves a considerable reduction in distracting artifacts while also enhancing diagnostic information.
SonoCT with XRES case study: splenic mass [8]
A 60 year old male presented for a CT examination to stage known metastatic lung cancer. Ultrasound was then recommended to clarify a poorly defined isodense splenic lesion seen with CT.

‘We find that the image quality generated with SonoCT imaging and XRES technology helps us to consistently diagnose with greater confidence

**Preliminary clinical results with XRES**

The XRES algorithm has so far been optimized for abdominal, OB/Gyn, breast, small parts, musculoskeletal and vascular applications, with care taken to enhance diagnostic features without deleting fundamental clinical information. Philips Ultrasound has implemented XRES in real time on standard 2D grayscale studies as well as on ‘frozen’ panoramic and 3D images. In 3D imaging, XRES can be applied to the fully rendered 3D volume as well as to the 2D slices used to generate the volume.

Like most image quality enhancements, the best way to determine their impact on the diagnostic process is through extensive clinical evaluation. XRES was first introduced as a feature on the Philips HDI 5000 SonoCT premium ultrasound system in October of 2001, and reports are now starting to be written regarding its value in assisting diagnosis. The following are extracts from some recent clinical case studies provided to Philips Ultrasound by customers.
with conventional imaging (Figure 5a), SonoCT imaging with XRES mode (Figure 5b) sharpens the image to allow full appreciation of the thrombus as well as posterior plaque within the aneurysm. In this case, we saw crisp delineation of the aortic wall and posterior plaque which enabled easier measurements.

**XRES case study: septated uterus** [10]
A 32 year old patient presented with a history of infertility and pelvic pain. Two previous ultrasound exams could not confirm either a septated or bicornuate uterus. Previous hysterosalpingogram revealed abnormal uterine cavity and obstruction of left fallopian tube. A gynecologic examination revealed a longitudinal septated vagina with two cervical os (one with each vagina).

‘Using XRES technology with the C8-4v transducer, the 2D image quality was noticeably sharper, specifically improving myometrial and endometrial echo texture (Figure 6). These subtle improvements in tissue texture enhanced our ability to detect muscular lesions (adenomyosis or small myomas) and/or small endometrial polyps that are critical in making an infertility diagnosis. In addition, the enhanced view of the coronal...'

**SonoCT with XRES case study: aortic stent endograft** [9]
This 87 year old female patient was seen in the vascular lab in routine follow up of aortic non-supported endografts. The patient had a history of hypertension, carotid artery disease, and a known 4 cm abdominal aortic aneurysm (AAA) found on CT. This was repaired with a bifurcated, single body construction, non-supported stent endograft.

‘The improved resolution of SonoCT images in XRES mode can shorten exam time by providing enhanced visualization with fewer artifacts than usually seen in abdominal vascular imaging. While you can see the endograft and residual AAA sac with conventional imaging (Figure 5a), SonoCT imaging with XRES mode (Figure 5b) sharpens the image to allow full appreciation of the thrombus as well as posterior plaque within the aneurysm. In this case, we saw crisp delineation of the aortic wall and posterior plaque which enabled easier measurements.’

**SonoCT with XRES showed sharper margins and borders, with better overall definition.**
plane using 3D imaging with XRES technology was essential in helping us to differentiate between the possible types of uterine malformations. In this case, 3D imaging in XRES mode helped us to make the final diagnosis of total septated uterus (body and cervix) that was not possible using conventional imaging. From a productivity and patient management standpoint, using 3D imaging with XRES mode is desirable because it is noninvasive, and exam times are shorter and less expensive than laparoscopy and hysteroscopy exams.”

Conclusions

XRES is the first commercially available real-time image processing algorithm for ultrasound that is truly adaptive to the content of the image. The adaptive nature of the algorithm allows it to smooth in regions of speckle or noise while preserving resolution and tissue texture, and enhance tissue interfaces without boosting noise. Early clinical evaluations suggest that it can play a significant role in improving contrast resolution (mainly through speckle reduction), improving border definition and continuity, and in reducing noise and clutter for better visualization of regions with low echogenicity. Existing diagnostic criteria appear to be preserved: often a key concern of clinicians presented with processed images. As has already been observed with SonoCT [11], it can be expected that these improvements in basic image quality will help to improve consistency of diagnosis by reducing both patient and operator dependence, and may ultimately improve diagnostic accuracy and confidence and increase patient throughput.

References

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