ultrasound technology update

Harmonic Imaging

Executive Summary

- Conventional ultrasound imaging sends out a burst of sound and listens for that burst to echo off of structures in the body. The time it takes for the echo to return is proportional to the distance the sound wave traveled.
- Instead of listening for the same sound burst to return in the echo, harmonic imaging listens for a sound burst at twice the transmitted frequency.
- Harmonic imaging has a number of potential clinical benefits including improved spatial resolution to permit visualization of smaller objects, and improved contrast resolution to improve demonstration of increasingly subtle differences in grayscale.
- The benefits of harmonic imaging will be most apparent in the mid-field - center portion of the ultrasound image.
- The benefits of harmonic imaging can be improved and extended by combining it with Maximum Resolution Ultrasound, a technique that improves lateral resolution by using wide imaging apertures.
- At the moment, GE Ultrasound is the only manufacturer that can provide the combination of these two technologies

Background/Overview

To understand the benefits of Harmonic Imaging, consider how it differs from conventional ultrasound imaging. With conventional imaging, the ultrasound system transmits and receives a sound pulse of a specific frequency (Figure 1). The difference between the transmitted and returned signal is that the returned signal is less intense, losing strength as it passes through tissue.

With Harmonic Imaging, on the other hand, the signal returned by the tissue includes not only the transmitted "fundamental" frequency, but also signals of other frequencies – most notably, the "harmonic"[1] frequency, which is twice the fundamental frequency (Figure 2). Once this combined fundamental/harmonic signal is received, the ultrasound system separates out the two components and then processes the harmonic signal alone.

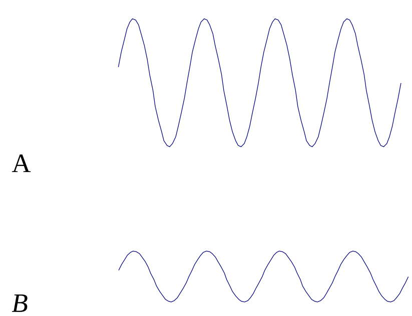

Figure 1 – In conventional imaging, the transducer transmits (A) and receives (B) sound waves of a given frequency. The received signal is lower in intensity because it is attenuated by the tissue.

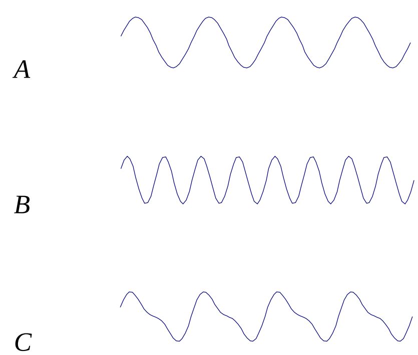

Figure 2 – In Harmonic Imaging, the returning signal (C) is actually a combination of frequencies. It contains not only the fundamental signal that was originally transmitted (A), but also the harmonic signal (B), which is twice A's frequency. The ultrasound system processes these signals separately.

[1] Various authors refer to this signal as either the "first harmonic" or as the "second harmonic." This naming convention is arbitrary and does not affect the physical principles illustrated in this paper.

GE Medical Systems

How Harmonics Are Generated

The harmonic signals used in this form of imaging do not come from the ultrasound system itself. These signals are generated in the body as a result of interactions with tissue or contrast agents.

Interactions with Contrast Agents

To generate harmonic signals using ultrasound contrast agents, the patient is injected with a contrast agent containing very small bubbles. A conventional ultrasound pulse is then sent into the body. When the pulse encounters the bubble it generates two kinds of responses. See Figure 3.

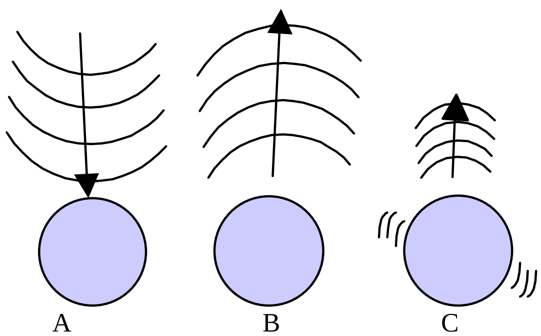

Figure 3

A. The pulse arrives from the transducer. B. The echo returns from the bubble. C. The bubble vibrates, generating another signal, the harmonic, which also returns to the transducer.

First, because of the difference in acoustic impedance, the pulse bounces off the interface between the bubble and surrounding tissue – just as it would in conventional imaging. But more importantly for the purposes of this discussion, the bubble vibrates in response to the shock from the pulse. This is much like a bell ringing when struck by its clapper. This vibration generates a harmonic signal at twice the frequency of the original ultrasound pulse.

This kind of imaging benefits from the fact that the only strong signal returning from the body at twice the fundamental frequency will be the signal that comes back from places where the bubbles are. By listening only for the ring of the bell, the harmonic signal, the ultrasound system can generate very high contrast images that are relatively free of the kinds of interference that makes conventional ultrasound imaging difficult. Figure 4 shows an example of this kind of imaging.

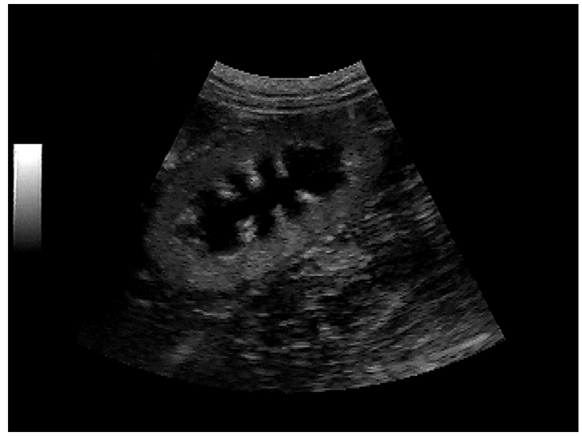

Figure 4 – Harmonic image of a kidney, formed by using a bubble contrast agent.

Interactions with Tissue

The presence of bubbles in the tissue, however, is not the only way in which harmonics can be generated. To understand this, keep in mind that when a nice clean sine wave is sent into the body, it is distorted and changed by the properties of the tissue through which it travels. You don't get a nice sine wave that travels through the body, encounters a tissue interface and then returns as a nice sine wave back toward the transducer.

Consider, for example, how the tissue can affect the speed of sound in the tissue. When tissue is compressed, the speed of sound generally increases in the compressed area. When the tissue is relaxed, the speed of sound decreases. A sound wave moving through the body is in fact a pressure wave. This pressure wave compresses and relaxes the tissue as it moves through it. Figure 5 illustrates this effect.

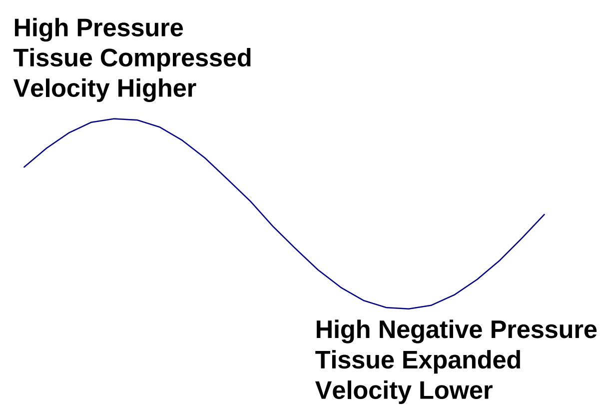

Figure 5 – As sound travels through tissue it compresses and expands the tissue. Where the tissue is compressed, the speed of sound is higher.

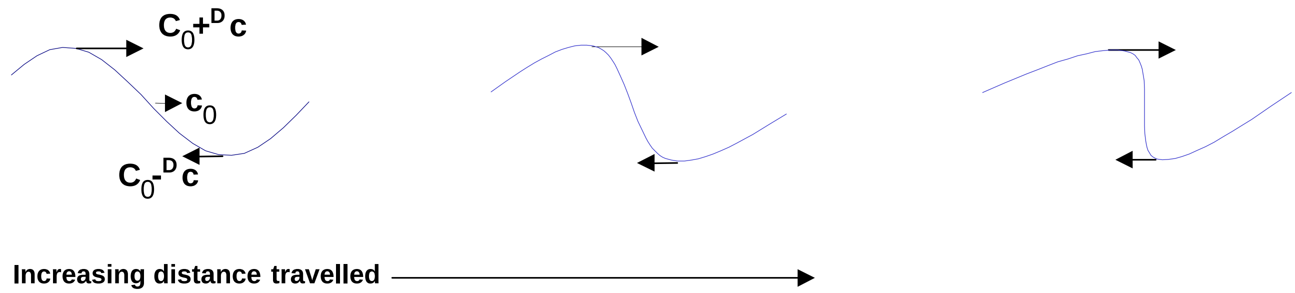

Figure 6

Because the speed of sound is higher when the pressure is higher, the top of the waveform gets pulled forward as the wave passes through tissue. This distortion of the waveform causes harmonics to be generated. Note that the bottom of the wave doesn't actually travel backwards, it travels forward at a slower speed. The arrows are for illustration only.

Since the speed of sound varies at different parts of the waveform, the nice clean sine wave is distorted. This distortion becomes more pronounced as the wave passes through the tissue. Figure 6 shows this effect. The middle of the wave moves at c_0, the nominal speed of sound. The top of the wave moves at $c_0+\Delta c$, a bit faster. The bottom of the wave moves at $c_0-\Delta c$, a bit slower. As the sound wave passes through the tissue, the top of the wave is pulled forward and the bottom of the wave is tugged backwards. Different tissues distort the wave in different ways. For instance, fat tends to distort the wave in this way much more strongly than does muscle, liver, or kidney tissue. Water, also has properties that cause this effect, but to a smaller extent. But whatever the tissue, the resultant waveform contains both the fundamental frequency plus harmonic frequencies caused by the distortion.

Compare the last waveform in Figure 6 with the last waveform in Figure 2. Note that the shapes are similar.

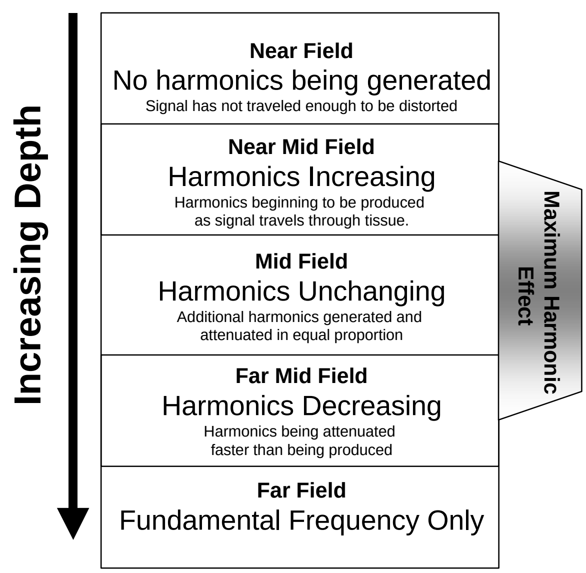

Figure 7 – The harmonic imaging effect is most pronounced in the mid field.

Just as the waveform in figure 2 could be "disassembled" into the fundamental and harmonic, the waveform caused by tissue distortion can be disassembled into a fundamental and harmonics.

This ability to create harmonics in tissue is an effect that is seen in varying degrees throughout the ultrasound field of view. See Figure 7. In the near field, the wave has not traveled sufficiently far to be distorted in the way described in Figure 6. As the wave moves into the mid field, the distortion in the wave starts to create harmonics. In the center, the harmonics are still being generated, but the effect of the attenuation of the signal by the tissue destroys as many harmonics as are created. Farther out, attenuation exceeds the harmonic generation, and at the extreme, only the fundamental signal remains.

As a result, the generation of harmonics without contrast agents will only be apparent in the middle of the ultrasound image.

Potential advantages of the harmonic signal.

Ultrasound beams formed with the harmonic signals have some interesting properties. One of those properties is that the beam formed using the harmonic signal is narrower and has lower side-lobes[2]. Figure 8 shows the beam profile from a conventional ultrasound beam, and from the beam formed from the harmonic signals. The improvement in beamwidth and reduction in side lobes will significantly improve grayscale contrast resolution.

Furthermore, since the harmonics are generated inside the body, they only have to pass through the fat layer once (on receive), not twice (transmit and receive). See Figure 9. The potential benefit of this effect may be reduced somewhat, however if the primary transmit beam is significantly affected as it passes through the fat layer on transmission.[3]

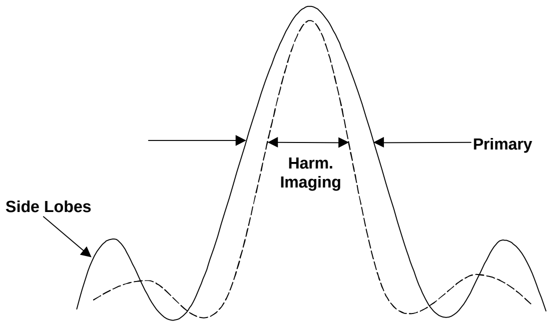

Figure 8

Harmonic beams are narrower than their conventional counterparts. Also, side lobes are lower. The result is improved spatial resolution and better contrast resolution.

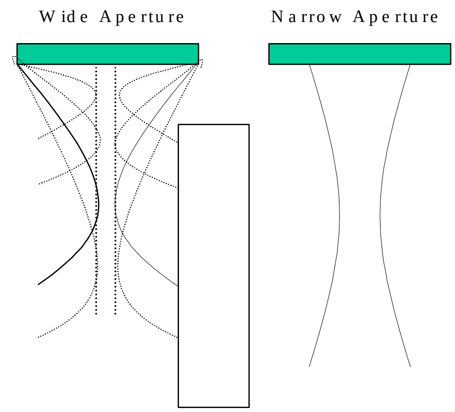

Figure 10 - Comparison of beam width using narrow aperture and wide aperture imaging techniques. Wider apertures combined with multiple focal zones will produce narrower beams and more harmonics.

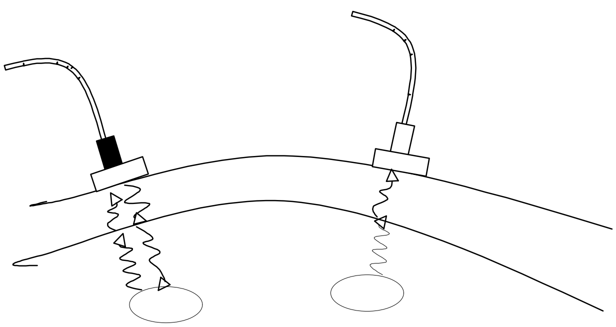

Figure 9 –Conventional ultrasound signals are negatively affected twice: on transmit and receive. Harmonic signals are only affected on receive because they are generated inside the body.

Aperture Size and Harmonic Imaging

The potential imaging improvements described above, of course, can only be demonstrated in images where harmonic signals are generated in the body. As shown in figure 6, the harmonics are generated in response to acoustic pressure. In general, more harmonics are generated when the acoustic energy is more concentrated.

The reason they are more prominent in the region of the transmit focus is that the ultrasound energy is more concentrated in this area. Where more energy is concentrated , the acoustic pressures will be higher. With higher pressures, the differences between the normal speed of sound in the tissue and the speed of sound in the compressed and expanded regions of the tissue will be greater. This will cause a greater distortion of the sine wave and the creation of more harmonics.

Aperture size is one of the parameters one can use to improve concentration of energy and the production of harmonics. In short, lateral resolution in ultrasound improves when the imaging aperture gets larger. (See separate technical paper on *Wide Aperture Imaging* from GE Medical Systems.) This improvement in lateral resolution is due to a narrowing of the ultrasound beam. See Figure 10.

In the case of single focal zones (Figure 10 right side), the imaging resolution and the generation of harmonics will be best at the point of the transmit focus.

In Maximum Resolution Ultrasound, a technique developed by GE in 1996, wide aperture techniques were further improved by providing up to 8 wide-aperture focal points in the image while maintaining reasonable frame rates. The result is that a narrow beam of concentrated ultrasound energy can be created that is uniformly narrow in the lateral direction. The beam implied by the space between the dashed lines of focus in Figure 10 is narrower than the beam for the conventional narrow aperture technique. In the context of harmonic imaging, this provides a double benefit because it produces a narrower beam (which improves resolution) and produces more energy in the harmonic beam (which has the imaging benefits described above.)

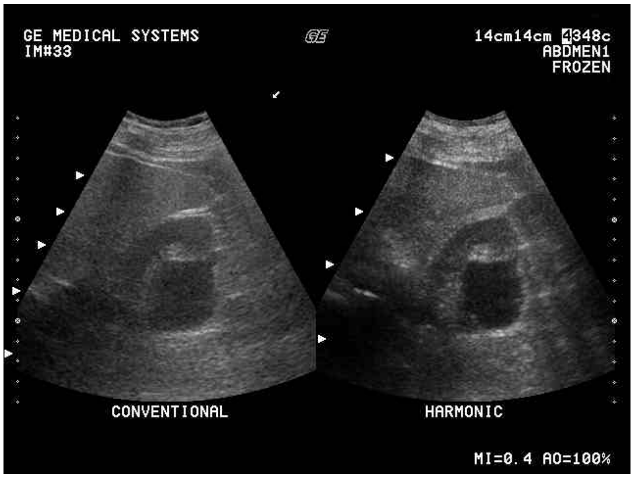

Figure 11 – Large renal cyst. Note the improvement in contrast resolution that is achieved with the improved slice thickness available with harmonic imaging.

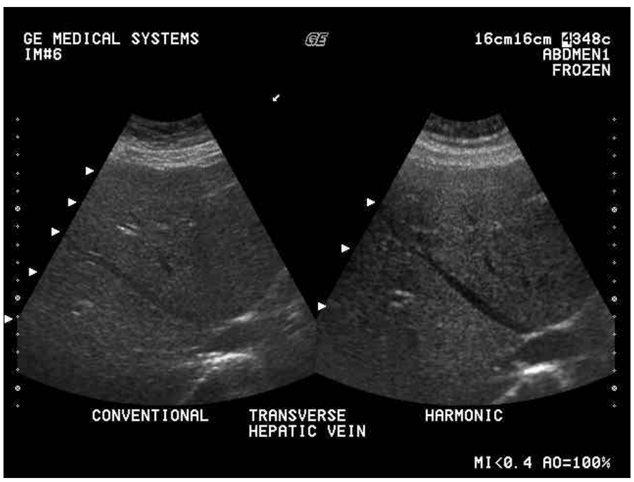

Figure 12 – Liver and hepatic veins. Note the improvement in cystic clearing in this vessel with Harmonic imaging enabled.

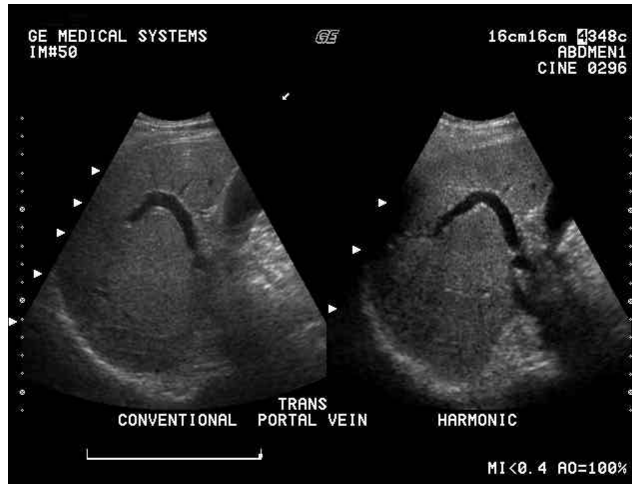

Figure 13 – Liver and Portal Vein. Note the improvement in penetration and contrast resolution with harmonic imaging turned on (right side).

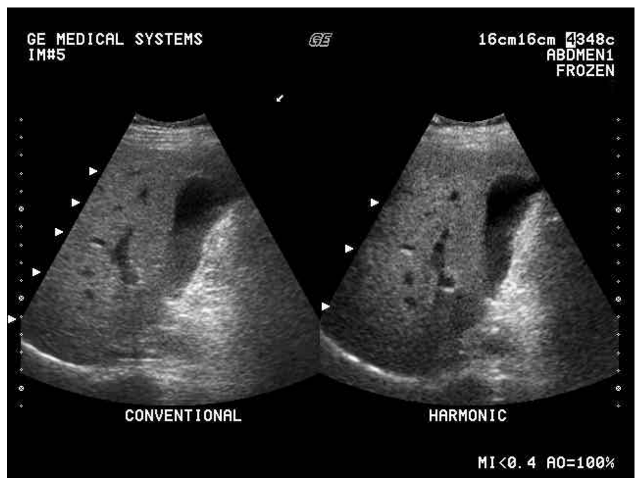

Figure 14 - Comparison of liver and gall bladder using conventional and harmonic imaging. Note the improvement in cystic clearing and penetration, the reduction of side lobes, and the elmination of pseudo-sludge in the gallbladder with Harmonic Imaging.

Summary

The properties of tissue cause the primary ultrasound signal to distort in the body. The distortion of this signal causes harmonics to be generated in tissue and these harmonics can then be used to generate an ultrasound image. The properties of these harmonic signals are such that one can get significant improvements in spatial and contrast resolution, but these improvements are limited to the region of interest in which the acoustic energy is sufficiently high to cause the harmonics to be generated.

The concentration of the acoustic energy can be controlled in several ways. Among them is the use of wide aperture imaging to produce narrow beams in the lateral direction.

Though several ultrasound suppliers have described commercial availability of harmonic imaging, as of the time of this writing, only GE Medical Systems (Waukesha, Wisconsin) has the ability to provide the combination of harmonic imaging with Maximum Resolution Wide Aperture imaging.

For more information on GE Ultrasound products, visit our web site at http://www.ge.com/medical/ultrasound, or call 1-800-458-1402.

Selected Bibliography

[2] B. Ward, A.C. Baker and V.F. Humphrey, “Nonlinear propagation applied to the improvement of resolution in diagnostic medical ultrasound,” *J. Acoust. Soc. Am*. 101 (1), 143-154, January 1997

[3] Ted Christopher, “Finite Amplitude Distortion-Based Inhomogeneous Pulse Echo Ultrasonic Imaging,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol 44, No 1, 125-139, January 1997.

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GE Medical Systems

GE Medical Systems – Americas: Fax 414-544-3384
P.O. Box 414, Milwaukee, WI 53201 USA

GE Medical Systems – Europe FAX 33-1-30-70-94-35
Paris, France

GE Medical Systems – Asia:
Tokyo Japan – Fax: 81-3-3223-8560
Singapore- Fax: 65-291-7006