THE EFFECT OF TRANSDUCER BANDWIDTH ON ULTRASONIC IMAGE CHARACTERISTICS

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Purpose: This study was conducted to determine the effect of transducer bandwidth on the characteristics of ophthalmic ultrasound images.

Methods: B-scan images produced using two transducers, one with a narrow bandwidth and the other with a broad bandwidth, both having nominal center frequencies of 10 MHz, were evaluated. Comparative scans were made of a tissue-mimicking phantom, an intraocular tumor, and a vitreous hemorrhage.

Results: Results showed that broadband transducers gave improved resolution and finer speckle texture, but had lower sensitivity. Broadband transducers were most suitable for situations in which resolution was more important than sensitivity, such as imaging of tumors. The greater sensitivity of the narrowband probe made it most useful for evaluation of vitreous complications, such as hemorrhage and membranes.

Conclusion: In addition to transducer frequency, bandwidth should be taken into account when choosing a transducer for a specific ophthalmic imaging application. Both broad- and narrowband transducers have relative advantages in particular applications.

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Ultrasound is the most widely used ophthalmic radiologic imaging modality. During the last year at the New York Hospital-Cornell Medical Center, B-scan ultrasonography was used for ophthalmic examination approximately five times more often than computed tomography and magnetic resonance imaging combined. Ultrasound instruments are relatively portable, inexpensive, and provide real-time imaging. They can accurately determine the dimensions of anatomic structures and pathologic changes in cases where optically opaque media prevent direct visualization.

Although it is generally appreciated that the axial resolution of ultrasound instruments improves with increasing transducer frequency, other transducer characteristics, including focal length, F-ratio, linear array versus mechanical sector scanning mode, and bandwidth, also have significant effects on image quality.[1] We conducted a study of the effect of transducer bandwidth on the characteristics of ophthalmic ultrasound B-scan images.

Background

The physics of diagnostic ultrasound has been described in a number of texts.[2,3] An ultrasonic trans-

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ducer contains a piezoelectric crystal, the thickness of which changes in response to a voltage pulse. This results in an acoustic pulse that will propagate through the fluid medium to which the crystal is coupled. Such a pulse may consist of one or more cycles of compression and rarefaction of the fluid medium. As the number of cycles per pulse decreases, the temporal (and spatial) duration of each pulse becomes shorter, and objects that are closer and closer together become individually resolvable. Because an acoustic pulse must have a minimum duration of one cycle, transducer frequency places a lower limit on spatial pulse length. Thus, if we only consider highly damped pulses of a single cycle, the generalization that resolution increases with frequency is correct.

Actual acoustic pulses emitted by ultrasonic transducers are not perfectly damped. As the number of cycles in each pulse increases, the temporal/spatial duration of each pulse increases and axial resolution must decrease. A long, poorly damped pulse, however, contains greater total acoustic energy than a short, highly damped pulse, and will therefore provide greater sensitivity.

While every ultrasound transducer has some nominal frequency, all transducers emit acoustic energy over a finite, continuous range of frequencies surrounding this nominal frequency. Spectrum analysis can be used to measure the pulse characteristics of ultrasonic transducers by expressing the amplitude of an acoustic pulse as a function of frequency. The range of frequencies present in the spectrum is referred to as spectral bandwidth.

Any signal varying with time can also be expressed, by use of the Fourier transformation, as an equivalent signal varying with frequency. The relationship between the time-varying or temporal form of an acoustic signal and its frequency-varying or spectral representation is illustrated in Figure 1. A continuous periodic signal, such as a sine wave, can be expressed in the frequency domain as a signal with all its energy concentrated at one frequency (Figure 1, top) corresponding to the number of cycles per second of the sine wave. Thus, a continuous wave (temporal domain) has an infinitely narrow bandwidth (frequency domain).

The opposite situation is that of an impulse, i.e., an idealized signal of infinitely short duration. In this case, the frequency domain representation has its energy spread over all frequencies (Figure 1, bottom), equivalent to an infinitely broad bandwidth. Realistic ultrasonic pulses (Figure 1, middle) must vary somewhere between these two theoretical extremes, but as the extreme cases imply, bandwidth increases as pulse duration decreases.

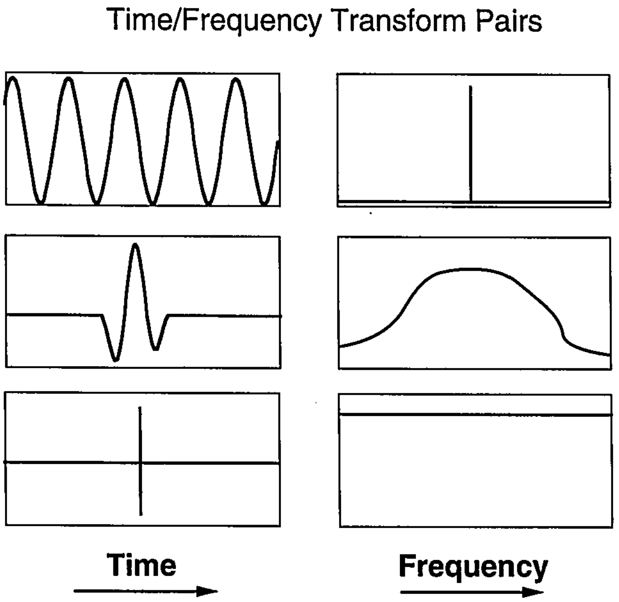

Fig. 1. Bandwidth refers to the range of frequencies comprising a signal. A continuous wave (top) has an infinitely narrow bandwidth, while an impulse (bottom) has an infinitely broad bandwidth. An actual ultrasonic pulse (middle) exhibits a finite bandwidth that decreases as pulse duration increases.

The effect of bandwidth on resolution is illustrated schematically in Figure 2. This figure compares broadband and narrowband echoes received by the transducer from two reflecting objects separated axially by distance *d*. When a narrowband pulse (top) with a pulse length greater than *2d* is partially reflected by each object, the combined echo will not allow resolution of the reflectors, *a* and *b*, as two separate objects. When a broadband pulse (bottom) of the same frequency is reflected by the two objects, the resultant echo allows resolution of two distinct reflectors.

We compared the characteristics of ultrasonic images taken test objects and ocular pathologic conditions taken with two transducers that had identical nominal frequencies (10 MHz) but significantly different bandwidths.

Materials and Methods

Scanning was performed using a Sonovision STT-100 ophthalmic ultrasound scanner (Sonocare Inc., Upper Saddle River, NJ). The scanner incorporates hardware and software, allowing digitization of unrectified radiofrequency echo data. This allows demonstration of the spectral characteristics of interchangeable mechanical sector B-scan probes. In addition, the instrument allows digitization, storage, and retrieval of B-scan images.

Two transducers with nominal center frequencies

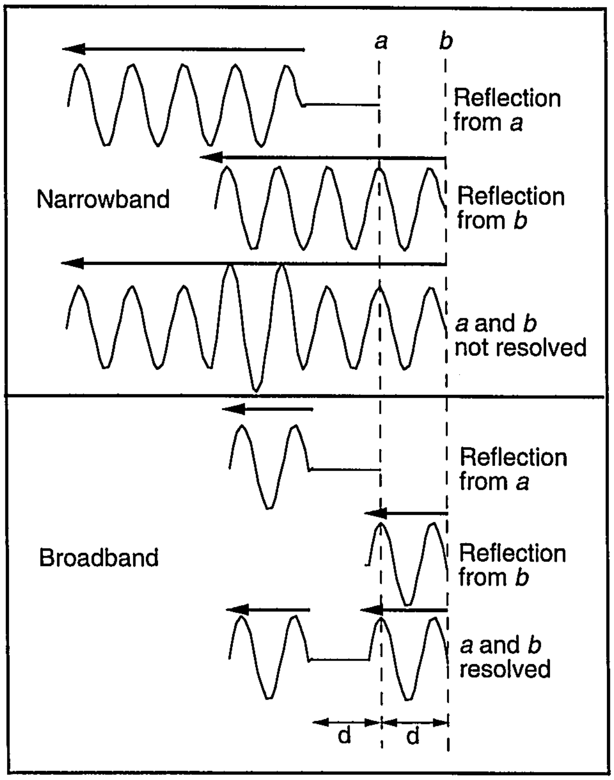

Fig. 2. Schematic illustration of the effect of bandwidth on axial resolution. Two reflectors, *a* and *b*, are separated axially by distance *d*. The uppermost trace shows the position of a narrowband pulse at time *d/v* after reflection from *a*, where *v* is the speed of sound. The position of the reflection from *b* at the same instant is shown in the lower trace. The sum of these waveforms, the echo eventually received by the transducer, shows interference effects (where the individual reflections overlap) and does not allow resolution of *a* from *b*. In the broadband case, the pulselength is less than *2d* and the combined reflected signals from *a* and *b* do not overlap. Arrowed lines represent the length of each pulse and the direction of travel of the reflected signal.

of 10 MHz (focal length = 2 cm) were evaluated. One transducer was highly damped and the other was only moderately damped. Transducer characteristics were determined by digitizing the reflection from a glass plate normally oriented to the transducer in the focal plane. The unrectified radiofrequency echo data were digitized at a 50 MHz sample rate. The transducer's power spectrum was then determined by taking the Fast Fourier Transform of the radiofrequency data and expressing its squared magnitude in decibel (dB) units as a function of frequency (MHz).[4]

Images made at five amplifier gain settings (100%, 90%, 75%, 65%, and 50% of maximum gain) were digitally recorded in each case. All scans were performed through a normal saline standoff, allowing placement of the area of interest in the transducer's focal zone. Scans of cystic zones in a tissue-mimicking phantom (Radiation Measurements, Inc., Middleton, WI), a pigmented tumor involving the iris and ciliary body, and a vitreous hemorrhage were made as described above.

Results

The digitized pulses reflected from a glass plate for each transducer are shown in Figure 3. The highly damped character of the broadband pulse is apparent when compared to the narrowband pulse. Figure 4 shows comparative power spectra of these echo traces. It is convenient to measure the bandwidths of these spectra at their −6 dB points, where spectral amplitudes are equal to half of their peak values. The figure shows that the narrowband transducer has a −6 dB bandwidth of 3.5 MHz (range = 7.1–10.6 MHz). In contrast, the −6 dB bandwidth of the broadband transducer is 7.7 MHz (range = 4.5–12.2 MHz). The spectra also indicate that at its peak frequency (9

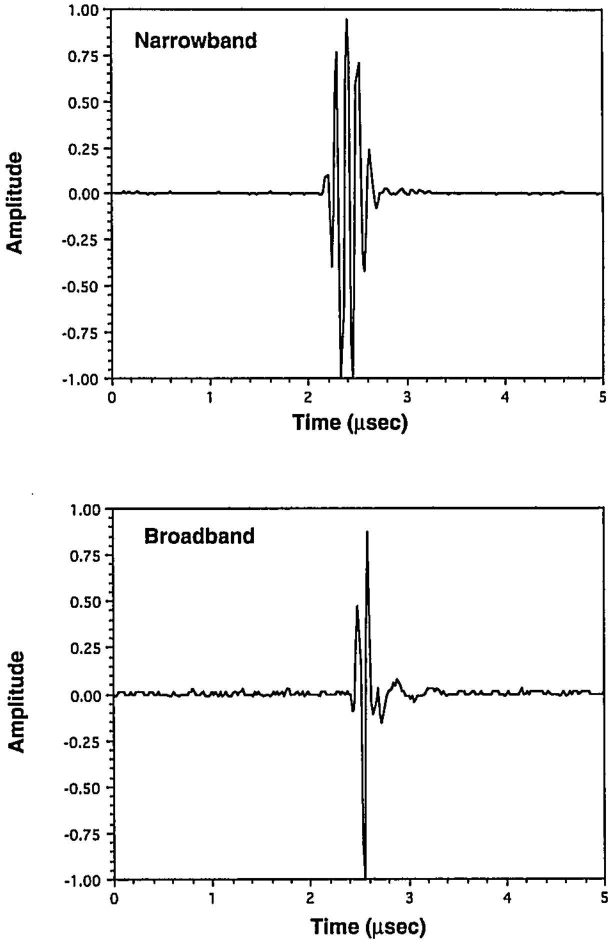

Fig. 3. Comparative reflected signals of narrowband and broadband 10-MHz transducers obtained by digitizing the reflected echo from a glass plate in the focal plane illustrate the more highly damped character of the broadband transducer.

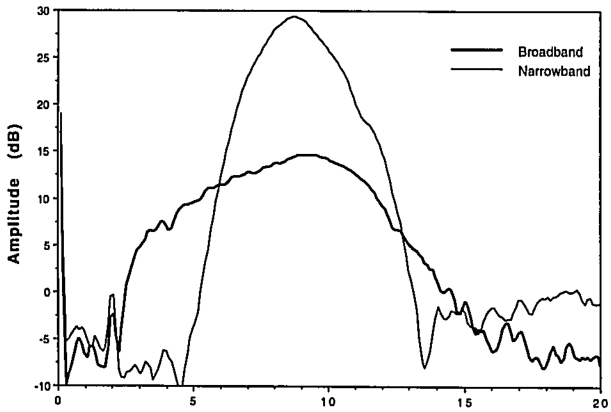

Fig. 4. Power spectra of the broadband and narrowband signals shown in Figure 3 illustrate the effect of pulse length on bandwidth.

MHz) the power spectrum of the narrowband transducer is nearly 15 dB higher than that of the broadband probe, indicating its greater sensitivity.

Comparative images made of cystic zones in a tissue-mimicking phantom are shown in Figure 5. Imaging characteristics were compared in terms of image brightness, sharpness, contrast, and texture. The narrowband and broadband transducers had comparable sensitivity with respective image gain settings of 65% and 100%. The narrowband transducer was more sensitive than the broadband transducer, but it produces images with a coarser speckle pattern and less discreet delineation of cyst boundaries.

Comparison of images of ocular pathologic changes taken with the two transducers revealed characteristics similar to those observed in the tissue phantom. Figure 6 shows images produced by the narrow- and broadband transducers of a pigmented tumor with cystic components involving the iris and ciliary body. These B-scan images demonstrate the same characteristics seen in the images of the tissue phantom, i.e., greater sensitivity with the narrowband transducer versus improved delineation of cystic components and boundaries with the broadband transducer. In fact, smaller cystic components seen with the broadband transducer are not resolved with the narrowband probe.

Comparative ultrasound images of a vitreous hemorrhage secondary to diabetic neovascularization are shown in Figure 7. This figure demonstrates a situation in which the sensitivity provided by the narrowband probe was more important than the better resolution provided by the broadband transducer. Faint hemorrhagic material that was barely detectable with the broadband transducer was easily visualized when the narrowband probe was used.

Discussion

Although ultrasound transducers are commonly characterized by their central or peak frequency, all transducers emit acoustic power over a discreet band surrounding this frequency. Frequency refers to the number of vibrations per second in any type of periodic wave phenomena, but does not by itself indicate the duration of the waves. A continuous periodic

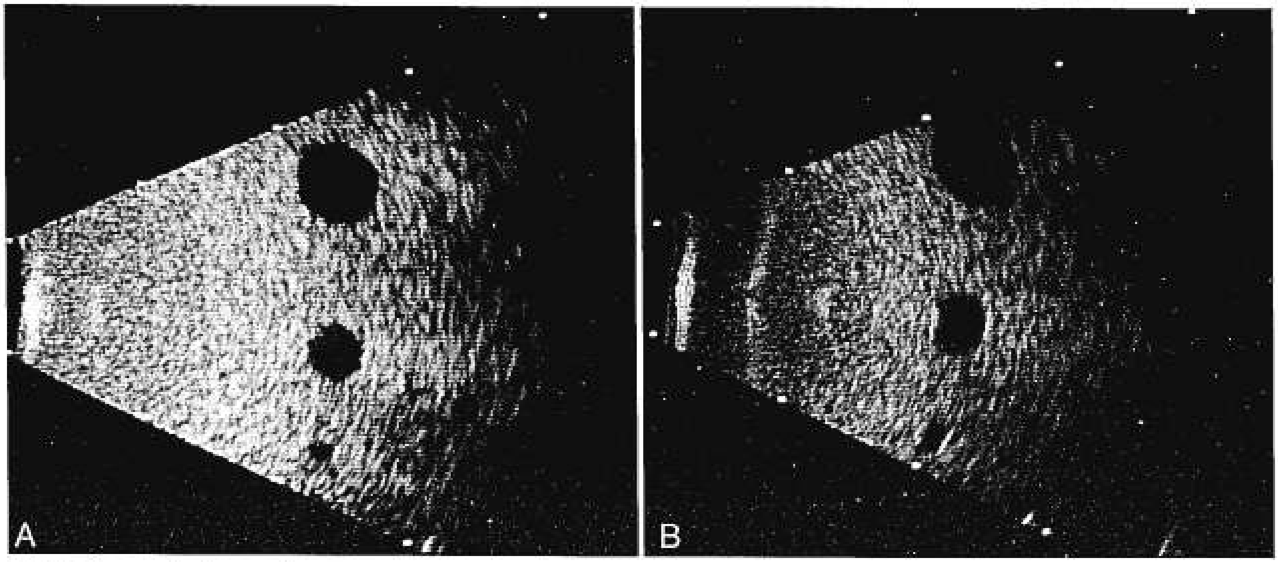

Fig. 5. Comparative images of cystic zones in a tissue phantom show the greater sensitivity and contrast of the narrowband transducer (A) versus the better delineation of the cyst boundaries and finer speckle texture of the broadband transducer (B).

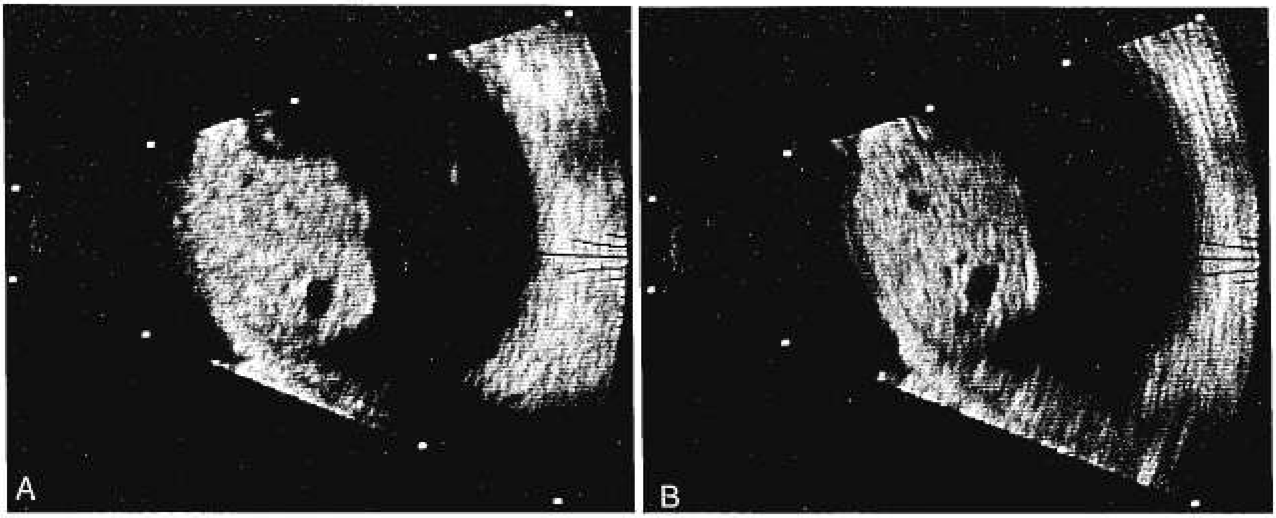

Fig. 6. Comparative images of a melanotic tumor involving the iris and ciliary body. The characteristics seen in the tissue phantom are also seen here: better delineation of cystic components and tumor boundaries with the broadband transducer (**B**) versus better contrast with the narrowband transducer (**A**).

wave signal has a narrow bandwidth, whereas a short pulse of waves has a broad bandwidth. The axial resolution provided by an ultrasound transducer is, by definition, one half of a pulse length. Thus, axial resolution improves with increasing bandwidth. As pulse length becomes shorter and bandwidth gets broader, however, less and less total power will be emitted in each pulse. Sensitivity therefore decreases as resolution increases. The net effect of this tradeoff is that two transducers with identical center frequencies and focal characteristics may produce images of distinctly different quality.

Speckle is produced by positive and negative interference of echoes reflected by objects within half a pulse length of each other. Our observation that narrowband transducers produce a coarser speckle pattern in both tissue phantoms and ocular tissues is consistent with this principle.

In addition to the above consideration, broadband transducers are particularly suitable for ultrasonic tissue characterization. Tissue characterization involves measurement of the scattering and absorption of ultrasonic energy as a function of frequency.[5] Ultrasonic scattering theory shows that the relationship be-

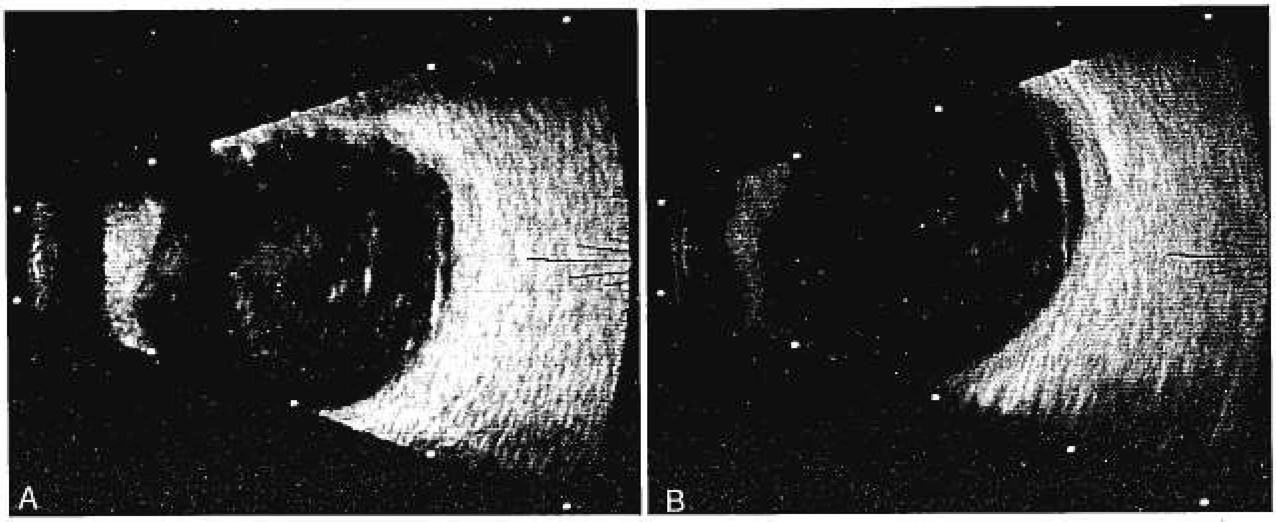

Fig. 7. Comparative images of a vitreous hemorrhage secondary to diabetic neovascularization illustrate a situation in which the greater sensitivity of the narrowband transducer (**A**) outweighs the superior resolution of the broadband transducer (**B**).

tween echo amplitude and frequency is determined by the size, acoustic impedance, and number-per-unit-volume of tissue inhomogeneities.[4] Because of the narrow range of frequencies emitted by narrowband transducers, they are not suitable for this purpose. The wide range of frequencies emitted by broadband transducers allows measurement of the effective size and concentration of tissue inhomogeneities (acoustic scatterers) using data from a single transducer.

We are studying the correlation between scatterer size and concentration with histopathologic features in uveal melanoma[6] and hyphema.[7] Additionally, we have described techniques based on spectral analysis for improved biometric accuracy in high-resolution ultrasonic corneal pachymetry[8] and quantification of corneal haze after excimer laser photorefractive keratectomy.[9]

The above considerations suggest that both narrow- and broadband transducers can play distinct roles in ophthalmic ultrasound imaging. Where maximum sensitivity and contrast are required (as in cases of a diffuse vitreous hemorrhage or veils), narrowband transducers produce images of superior quality. For imaging of solid tissue components where maximum resolution is desired and for biometric precision, however, broadband transducers are optimal. Ideally, both types of transducers should be readily available and interchangeable during the course of a clinical ultrasound examination.

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