Nonlinear effects - Safety Aspects

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Basic Terminology

ARFI – acoustic radiation force imaging

CEUS – contrast enhanced ultrasound imaging

finite amplitude – the effects of nonlinearity are amplitude dependent, and referred to in acoustics as "finite amplitude" in comparison to linear theory, where infinitessimal amplitudes are assumed.

harmonics – a harmonic is defined as an integer (whole number) multiple of the fundamental frequency (e.g. 6 MHz is therefore the 2nd harmonic of the fundamental frequency of 3 MHz).

nonlinear – if a system acts nonlinearly, then the output is not proportional to the input.

Introduction

The propagation of ultrasound waves is fundamentally a nonlinear process, and only waves with infinitesimally small amplitudes may be described by linear theory (which is the classical fundamental design assumption for imaging equipment). In practice, with modern equipment, all ultrasound emission is associated with a progressive distortion in the acoustic waveform and the generation of harmonics of the drive frequency and/or acoustic shocks, excess deposition of energy, and acoustic saturation [1-3]. Nevertheless, today, nonlinear effects are necessary for harmonic, contrast-enhanced (CEUS) and ARFI imaging, and are also important in interactions with contrast agents [4]. In acoustic output measurements it is essential to obtain a realistic knowledge of the physical characteristics of the ultrasound field to which the tissue is exposed by investigating nonlinear effects to get a proper assessment of safety for modern diagnostic ultrasound applications [5,6].

Basic Science

Finite amplitude effects and nonlinearity

When a wave on the surface of the sea moves in towards the shore it changes in form. Starting from a sinusoidal, up and down motion, the crests of the waves slowly catch up with the troughs preceding them, ultimately forming a "*breaker*" when the wave peak overruns the trough. Shallow ripples do not show this effect, being very small in amplitude, but the greater the height of the wave, the greater the chance of a breaker forming: this is an effect resulting from the "*finite amplitude*" of the wave, classical linear relationships break down and nonlinear effects occur.

The ultrasonic pulses propagating from a medical ultrasound transducer behave in a way comparable to sea waves. The compression part of the wave moves faster than the preceding decompression, and steadily catches up with it (Fig.1).

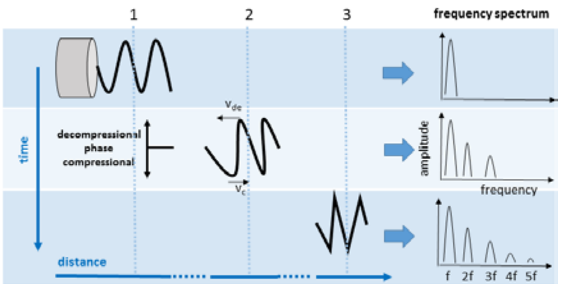

Fig.1: Progression of the wave shape over time and with distance, showing the development of nonlinear effects

1: a pure sine wave of frequency f is emitted;

2: with time and distance the sine wave begins to distort because the compressional wave phase v_c is faster in velocity than the decompressional phase v_{de} and harmonics (2f,3f) are generated.

3: finally a "sawtooth" wave, rich in harmonics, develops.

Again, this is a finite amplitude effect, and occurs to a greater extent in high amplitude pulses than it does in lower amplitude waves. (Indeed, the effect may be ignored for continuous-wave Doppler beams).

Ultrasonic waves differ from surface waves, however, at the point where the crest has just caught up with the trough of the wave. The ultrasonic pressure wave cannot "*break*" as a sea wave can. Instead it forms a "*shock*" where the compression follows very closely behind the decompression ("sawtooth"), the change from peak to trough happening in fractions of nano-seconds, rather than in fractions of micro-seconds.

Nonlinearity coefficient ß

Nonlinear effects occur during the transmission of the finite amplitude wave not only in water but also in biological tissue. For these media the nonlinearity coefficient ß = 1+B/2A (B/A being the parameter of nonlinearity of the medium) fall in the range of 3-7 (water to fat), while contrast agents show coefficients of more than 1000 at high concentrations [7,8]. As a consequence of nonlinear propagation harmonics are generated, shock waves are developed and in general the attenuation of this ultrasound wave in tissue is greater.

Nonlinear propagation parameter σ (formerly known as the shock parameter)

A simple parameter ($\sigma = 2\pi/\rho_o c^3 \, [p_o f z\,(1+B/2A)]$) is used to describe how *"shocked"* the wave has become. For a simple plane continuous wave σ increases linearly with the distance the wave travels, z, the frequency f, the acoustic pressure at the source of the wave p_o and ρ_o the density of the medium. σ describes how far the peak positive and negative pressures deviate from the positions they would have in a pure sine wave for which σ is 0. The wave can only be considered as being linear for $\sigma < 0.1$, while for $\sigma = 1$ the wave is just shocked and a σ of 3 is con-sidered as a fully distorted "saw-tooth" waveform [9].

Energy content of harmonic frequencies

The distortion of the wave can also, and equivalently, be described by an alteration in the frequency spectrum. A wave which starts out as a single frequency sinusoidal oscillation will carry progressively more energy at harmonic or multiple frequencies. For example, a 3 MHz wave will develop a spectrum which will include 6, 9, 12 MHz and higher frequency compo-nents.

Once a shock wave has formed, further propagation diminishes because the medium absorbs energy from the higher frequencies more strongly. It is as though the wave is being presented with an invisible barrier and energy is lost as the shocked wave continues to propagate. Ultimately, for a fully shocked saw tooth wave, the intensity of the second har-monic is 25% of that in the fundamental. In our example the energy in the 3, 6, 9 and 12 MHz components will be approximately in the ratios 1.0; 0.25; 0.11; 0.06. (This decreases as $1/n^2$, where n is the number of the harmonic, 1st, 2nd etc.)

Safety Implications

The changes in waveform caused by finite amplitude effects can occur readily in pulsed medical ultrasound fields within a few centimetres from the transducer. The combination of high frequency, together with the focusing used in imaging, results in conditions that can readily give rise to shocks in water, and potentially to some effects in vivo.

Broadly, nonlinear effects are important in two areas: for output measurements and for biophysical interactions.

Biophysical interactions

Enhancement of heating from the absorp-tion of harmonics in the beam has been recognised in diagnostic applications as well as for hyperthermia. There is less evidence for the formation of fully shocked waves in vivo than there is in water. This is because shock formation is inhibited by the tissue's greater attenuation of the high frequencies produced. On the other hand, large fluid volumes in vivo may well support shock formation. Amniotic fluid, blood and urine are clear candidates, with potential also in other low loss tissues such as brain, developing fetal tissue or aqueous/ vitreous humor. If harmonic generation occurs in such tissues the absorption of energy will be higher than would be expected under linear conditions, because of the greater energy loss from high frequencies. Consequently the resultant tissue heating may be greater for any given in situ intensity. It has been predicted and confirmed experimentally that a maximum enhancement factor of 3 in heating can be expected from this cause and corresponds well with the value of the nonlinear propagation parameter. Under conditions of nonlinear propagation, the maximum heating migrates toward the prefocal region in a homogenous tissue and the greatest enhancement might occur beyond a low-loss fluid path, conditions existing during obstetric scanning.

At present it would appear that cavitation is not strongly affected by the presence of non-linear wave distortions. There is some evidence that the amplitude of the fundamental in a distorted wave might be

the most relevant quantity predictive of cavitation potential.
The presence of acoustic shock significantly enhances the velocity of acoustic streaming generated by diagnostic pulses because of the greater transfer of momentum from the beam to the fluid through excess absorption [9].

Hydrophone output measurements

Water is the standard transmission material used for hydrophone output measurements of acoustic fields with linear models being used to estimate the *in-situ* exposure today. The problems arising with this current standard approach is the followings [9]: there is no correction for the excess energy loss that occurs during free-field exposure measurement in water, nor a correction for waveform distortion resulting from harmonic generation in water. In addition, possible nonlinear propagation effects *in vivo* are not estimated and the temperature rise (thermal index TI) does not account for increased deposition of energy from harmonics.
However, detailed prediction of nonlinear effects relating to diagnostic imaging output measurements requires further development and computing power-intensive numerical methods to validate the safe use with a greater accuracy.

Conclusions and recommendations

Medical ultrasonic pulses do not propagate according to linear laws. Nonlinear propagation results in waveform distortion, shock generation and unusual depositions of energy. Values of exposure quantities for ultrasound equipment obtained using hydrophones in water should be interpreted bearing in mind the potential for shock loss during the measurement. Whilst shock generation is mainly inhibited in soft tissues, conditions may well arise in fluids in vivo where pulses rich in harmonics could be found. Absorption of such pulses in soft tissues would give rise to heating enhanced by a factor of up to 3.
Follow the ALARA principle for setting the output and keep in mind that the displayed MI/TI values do not account for nonlinear effects.

References

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