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The Silent Revolution:

Catching Up With the Contemporary Composite Transducer

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Although a remarkable signal-processing evolution has been going on in the sonograph, a more silent revolution has been going on within the scanhead with the development of composite multielement transducers (CMETs). This article examines the current state of CMET development and explores what these changes mean to basic beam formation and focusing. The discussion reveals some of the technologies that are part of contemporary CMET design, including transducer *poling*, *connectivity*, and *coupling*. In addition, this discussion includes some quality assurance (QA) techniques that can test these new transducers for proper function and determine what is happening beneath the scanhead housing. Finally, the authors propose a list of measurements needed to test CMETs, including *element sensitivity*, *element center operating frequency*, *element fractional bandwidth*, *pulse shape*, *pulse duration*, and *element and cable capacitance*, and they provide a QA testing protocol for the CMET.

Key words: ultrasound, transducer, multielement, composite, quality assurance, poling, connectivity, coupling, beam forming, beam steering

The process of keeping track of technical developments in diagnostic sonography and image quality has been one of witnessing steady refinements in technology punctuated by sudden improvements in signal-processing architecture. Most of the recent changes, both large and small, have been the consequence of that great phrase “going digital,” that is, applying established digital signal processing (DSP) to the formation and enhancement of the gray-scale image. DSP has also made it possible to depict blood flow patterns within the cardiovascular compartments in real-time color. These imaging changes have been so remarkable and so successful that, in a way, it has been like a magician’s sleightof-hand trick. We have been visually drawn to watching the more colorful moving hand (digital signal processing) while missing the movements of the other hand (continued transducer development).

These transducer changes have not been as obvious as, say, a new and unique circuit board design or the real-time image of blood flow in color. Yet, we have witnessed a steady increase in transducer flexibility and capability along with a proliferation of new transducer designs that are specialized toward explicit scanning tasks. A silent revolution has been going on inside that scanhead housing. The transducer is no longer a simple, single-element device that either works or does not. Instead, current transducers have become more discrete in a different sense. The transducer is now a set of small, discrete elements that are electronically orchestrated into various wavefront geometries to form, focus, and steer an ultrasound beam. In this expanding mechanical complexity, current transducer designs seem to have surged ahead of our technical abilities to test the element arrays. Also, many subtleties of failure that may have an impact on the clinical study are not to be found with the conventional tissue-mimicking phantom (TMP).

This article examines the current state of transducer development and explores what these changes mean to basic beam formation and focusing. The discussion reveals some of the technologies that are part of the contemporary composite multielement transducer (CMET). In addition, this discussion includes some quality assurance techniques that can test these new transducers for proper function and determine what is happening beneath the scanhead housing. Finally, we propose a listing of measurements needed to test CMETs and pose a testing protocol to provide CMET quality assurance.

We begin with a set of useful definitions shown in Table 1.

Essential Transduction

At the functional center of any scanhead is the transducing material that converts energy from one form into another. For diagnostic sonography, it is a piezoelectric (PZ) substance organized to convert mechanical energy (pressure) into electrical energy (echo signal) and vice versa. This property emerges from the internal molecular organization of the PZ material. Applying pressure to the material causes the internal electric dipoles to reorganize, creating an electric field across the transducing element.[1] These electric dipoles also respond to an external electric field. As a result, a PZ material will change shape in response to an externally applied electric field.[1]

For diagnostic ultrasound, the organization and direction of the dipoles or *poling* is typically along the *z*-axis (Fig. 1), which is the same direction as the mechanical vibration of the transducer. The natural resonant frequency of a single-element transducer is set by its thickness, t, which is obtained by lapping the transducer to $\lambda/2$, where $\lambda = c/f$; c is the characteristic, acoustic propagation velocity for the PZ material, and f is the center operating frequency (COF) in Hz. The functional goal in designing for a natural vibration is to have the transducing wafer act as if it were a perfect piston. We expect to witness the natural resonant frequency of a transducer when it is shocked into natural vibration by a sharp electrical pulse rather than driven by a pattern of reversing voltages and currents (AC).

Common Events for Transducers

The basic role of the scanhead in a pulse-wave (PW) sonograph is to transmit a burst of ultrasound and receive ultrasonic echoes on a cyclic basis. The burst of ultrasound is amplitude modulated by the transmitter excitation technique and any internal transducer damping used to shorten the burst duration. The result is a fractional bandwidth (FBW) of frequencies within the ultrasonic burst.[2]

In simple terms, the sonograph is designed to form a focused beam of ultrasound and laterally move (scan) that beam over the image field-of-view to form a 2D, B-mode image of the echo sources in tissues. In the case of a PW system, the scanhead forms a focused virtual beam (V-beam). The beam is “virtual” in the sense that the sonograph is operating on an alternating pulse-listen cycle, although we tend to visualize the beam as if it were “on” all the time.

From a focusing point of view, the effective V-beam shape is formed by the multiplication of the

Table 1.
Selected Useful Definitions

Acoustic lens	An acoustic lens applied to the transducer face to provide mechanical focusing along the transducer azimuthal dimension
Backing material	Acoustically absorptive material to dampen transducer vibration
Center operating frequency (COF)	Median frequency between the –3 dB upper and lower intensity limits
Connectivity	The continuity of any material, both piezoelectric and polymer, within a composite transducer along the three transducer axes
Coupling	The ability of the transducer to transfer acoustic energy from the transducing material into the tissues
Ferroelectric material	An iron-based material that responds to external electric fields by forming physical, electric dipoles
Natural resonant frequency (NRF)	The natural resonant frequency defined by the half-wave thickness of the transducer
OEM	Original equipment manufacturer
Poling	The directional alignment of electric dipoles within a piezoelectric material
Polymer	The acoustically absorptive material surrounding the transducer elements
Piezoelectric (PZ) material	The transducing material that converts electrical to mechanical energy and vice versa
Quality assurance	A testing protocol that ensures the performance of the transducer and sonograph
Quality control	A testing protocol ensuring that “good manufacturing practices” are used to establish the quality of the manufactured product
Quarter-wave layer	A material applied to the transducer face with an acoustic impedance between that of the transducer and the tissues to increase transducer efficiency
Scanhead	A term applied to the complete transducer assembly, including cable, housing, and wear surfaces
Sonograph	An echo-ranging and/or Doppler device used to form gray-scale and color images for medical diagnosis
Transduction	The conversion of electrical to mechanical energy and vice versa
Virtual beam	The propagation path from the transducer face that the ultrasound waves would follow as if the system were transmitting continuously
Fractional bandwidth (FBW)	Transducer or signal bandwidth expressed as a percentage of the transducer COF
Wear surface	The surface material on the front of the transducer that is in direct contact with coupling gel and the patient’s skin

transmit focusing and the *receive directivity* produced by the transducing element.[2] Because of this multiplicative property, system designs can use very different focusing parameters for the transmitting and receiving portions of the pulse-listen (PL) cycle. Transmit focusing controls the ultrasound intensity coupled into the tissues by controlling the total transmit energy and the beam focusing within the focal zone. The transmit focal zone, however, can occupy only one range position in the V-beam on each pulse-listen cycle. Receive focusing, on the other hand, does not affect the energy intensity but can be very dynamic when the region of receive focusing slides along the V-beam, tracking the echo sources. Despite the fact that only ultrasonic bursts travel up and down the V-beam, the bursts generally behave as if they were confined to a real, continuously formed beam.

Affecting both transmit and receive focusing for a single element system is the transducer *aperture*, which represents the effective transducer area available to produce and collect ultrasonic energy (Fig. 2). For a multielement array, this same total area is set out by the number of individual

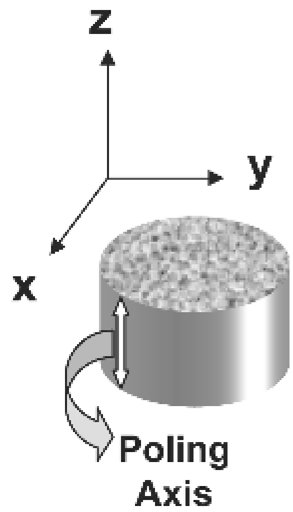

FIG. 1. Transducer poling is along the *z*-axis to provide vibration in the thickness mode.

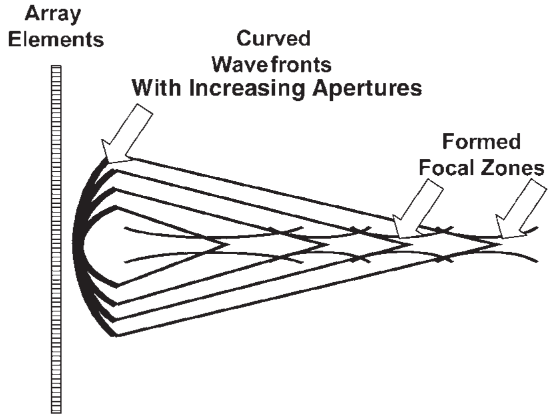

FIG. 2. To keep the same degree of focusing over more distant ranges, the system must recruit more transducer elements to increase the effective aperture.

transducing elements working in concert. For both single-element and multielement arrays, all focusing occurs within the transducer near field, expressed by the near-field boundary (NFB) equation:[3]

$$\text{NFB} = D^2/4\lambda,$$

where NFB is the range of the near-field/far-field boundary, D is the aperture diameter, and λ is the ultrasound wavelength. This equation describes the behavior of transducers ranging in size from λ/2 to 10s of wavelengths in diameter. For a single-element transducer, D is the diameter of that single element. For multielement transducers, however, the value of D is the diameter of the set of active array elements along the array length. The NFB is a valuable consideration for any transducer assembly because all focusing occurs within the NFB range.

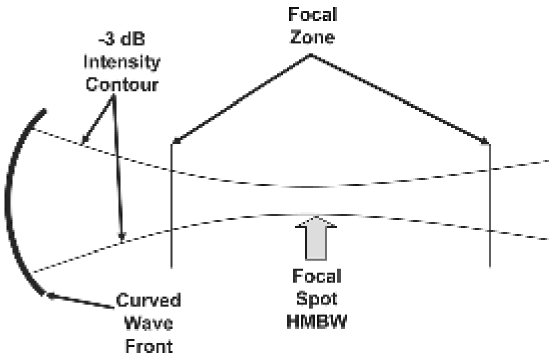

FIG. 3. Half-maximum beam width (HMBW) is defined by the –3 dB intensity beam width intensity contour. The focal zone is defined by another intensity decrease by half (–3 dB).

The degree of effective focusing is expressed by the half-maximum beam width (HMBW) for the transducer. The HMBW expression is as follows:[4]

$$\text{HMBW} = 1.22\,[\lambda/D]\,\text{Fz},$$

where λ is the operating frequency wavelength, D is the aperture diameter, and Fz is the range of the focal spot. This equation shows that as the range of focus increases, the *degree of focusing* becomes less and less. This equation expresses the expected focusing for a specific frequency. Because of the transmit FBW, however, the focal spot for the V-beam is not sharp but becomes a blur of focal spots (Fig. 3).

Scanning Goals and Ultrasound Beam Control

Beam formation for gray-scale imaging centers on determining the size, shape, position, texture, and dynamics of organs and masses in soft tissue. These implied measurements depend on the resolving abilities of the focused beam and the PW burst length. The focusing comes from the formation of a curved wavefront that advances to the geometrical beam focal spot. The lateral thickness of the fo-

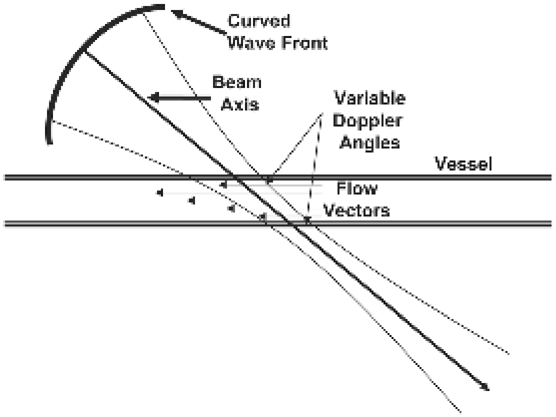

FIG. 4. Because of the beam shape, the composite beam rays intercept the flow vectors at a variety of Doppler angles, broadening the resulting spectrum.

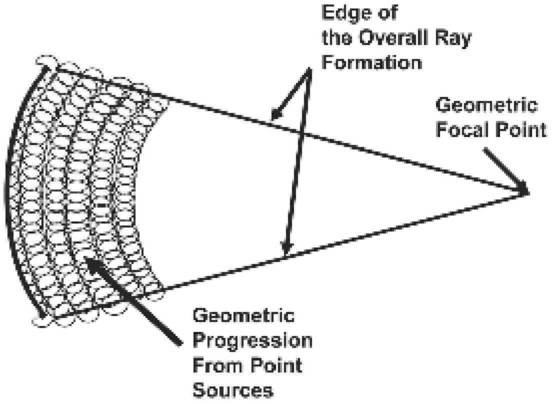

FIG. 5. Huygens's principle predicts the geometric formation of curved wavefronts that advance to a geometric focal point.

cused V-beam defines the *lateral resolution* for the image, where the best resolution is located at the focal spot.[3] The ultrasonic *burst duration* defines both the *axial resolution* in the image and the ultrasonic burst FBW.[5] The shorter the burst, the greater the bandwidth and the better the axial resolution.

In contrast, the imaging tasks for vascular Doppler ultrasound are to identify the source of the Doppler echo signals, determine the form of the flow over time, determine the frequency content of the flow over time, and determine the direction of the flow relative to the transducer and the vascular anatomy.[6] PW Doppler uses a sampling range gate and the ultrasound sample volume to define the region for signal processing to measure changes in echo signal frequency as a function of motion relative to the ultrasound beam. The lateral shape of the beam and the axial burst shape and duration define the effective Doppler *sample volume*.[7]

Beam focusing directs different parts of the beam toward a common focal spot. As a consequence of the ever-present beam width, not all parts of the ultrasound beam intersect all parts of the blood flow vector at the same angle (Fig. 4). The tool to use to look at these events is the Doppler equation, which not only permits calculating specific Doppler shift frequencies and echo source velocities as a function of the Doppler angle but also shows the variability of observed frequencies with changes in the Doppler angle. The Doppler frequency (Df) equation appears as

$$\mathrm{Df} = 2\ \mathrm{Fo}[V/c] \cos\theta,$$

where Fo is the COF for the Doppler system, V is the echo source velocity, θ is the Doppler angle, and c is the velocity of propagation for ultrasound. The Df function is slow-changing near $\theta = 0°$ but changes rapidly as θ approaches 70° and greater. In general, clinical vascular practice often sets the angle of the beam at 60° with the vessel wall.[8]

The Geometry and Behavior of Focusing

At the center of understanding the geometry of the focusing process is *Huygens's principle*, for both single-element and multielement transducers. Essentially, the transducer must form a curved acoustic wavefront that points the component wavefronts in the right direction (Fig. 5). We can trace the geometry of this focusing by following the propagation rule that each point on a composite wavefront acts as if it were a point source for the advancing ultrasonic waves.

In addition to forming a primary wavefront, any shaped transducer acts as if it were a diffracting hole in space. This diffraction process produces *side lobes* that direct a portion of the traveling wave energy away from the main lobe (Fig. 6). This is the same phenomenon we witness as light passes though a small hole in paper. For ultrasound, this side lobe production depends on the dimension of the transducer relative to its COF.

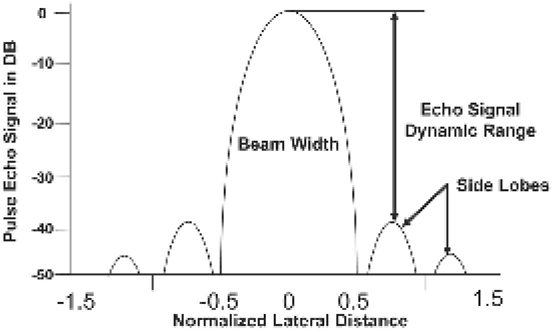

FIG. 6. The transducer element acts as a diffracting aperture that forms side lobes that affect the dynamic range of the transducer.

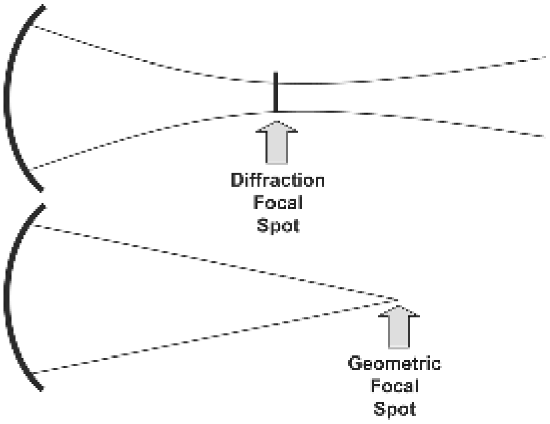

FIG. 7. The geometric model for beam formation does not include aperture diffraction events. As a result, the actual beam focuses closer to the transducer than the geometric model.

The diffraction process also tends to pull any beam focusing closer to the transducer than predicted by a pure geometric focusing model such as Huygens's principle.[9] This difference comes from the diffracting properties of the transducer (Fig. 7).

If we collect a set of sequential elements into a single aperture, losing a transducing element (or three) in an array removes the ability to balance the wavefront formation, leading to "acoustic spikes" within the expected wavefront. These distortions of the beam can produce some unanticipated image artifacts for both imaging and Doppler signal processing.

The Composite Transducer

Transducer array design can use either a single ceramic material or a composite of two materials to form the scanhead design. The *composite transducer* design centers on two components that combine to achieve a level of functionality that is unavailable to a single-compound transducer.[5] Most of the current composite transducers for diagnostic ultrasound are two-material arrays: (1) a PZ material that performs the basic transduction and (2) a polymer that shapes the physical and electrical performance of the PZ material.[5]

The composite transducer can be a 1D or 2D array of piezoelectric material surrounded on two or more sides by a relatively soft polymer.[5] This polymer provides electrical and acoustic isolation between adjacent vibrating elements. In action, the polymer acts like a shock absorber for the stiffer PZ material.[5] Adding the polymer is like placing shocks alongside the springs of a car. The polymer not only reduces the duration of the transducer vibration but also reduces all but the thickness mode of vibration of each transducer element.

Composite Transducer Construction

Constructing a composite transducer centers on a process called "dicing and filling."[5] Construction begins by casting a single piezoelectric block into a shape that will eventually permit the production of individual elements when the block is diced. This PZ bar is then diced into a set of smaller geometric elements that are connected to a common spine of transducer material (Fig. 8).

These sawed or "diced" regions are then filled with the polymer, extending beyond the ends of the PZ elements (Fig. 8).[5] Lapping the composite array on both the front and rear faces removes the surplus polymer from the face of the array and the PZ material spinal connection on the back side (Fig. 8). This leaves an array of individual PZ elements held by the interstitial polymer, where each element is able to vibrate in its own thickness mode. By carefully controlling the thickness of the isolated transducer elements, the lapping sets the array COF. The next steps are as follows: coating the front and rear with conducting electrodes, attaching any

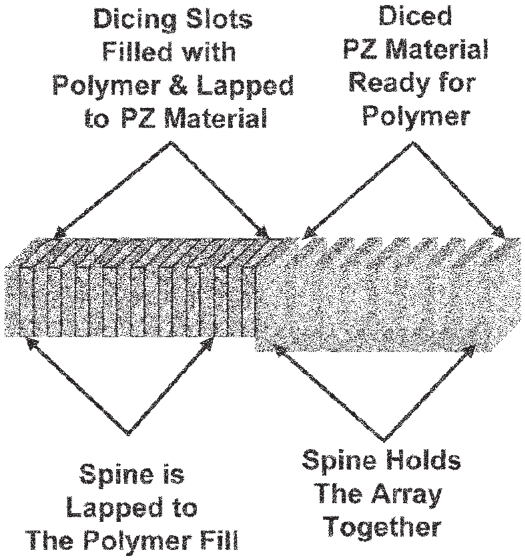

FIG. 8. To create a composite array, the piezoelectric (PZ) bar is diced, leaving a PZ spine to hold the element spacing while filling the dicing space. The spine is lapped away to the polymer fill, and the polymer is lapped to the PZ face.

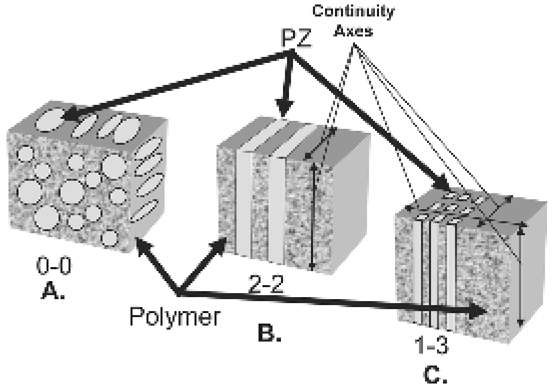

FIG. 9. There are three basic piezoelectric (PZ) polymer organizations for current composite transducers. (A) A random mix of PZ and polymer. (B) An array with two continuity axes for both materials. (C) Three axes of continuity for the polymer.

backing material, attaching the quarter-wave layers, and attaching a geometric lens for slice-thickness focusing.

Transducer quality control focuses on uniformity in (1) the uncut PZ material, (2) poling for the PZ material, (3) the polymer distribution, and (4) attachment of the polymer to the PZ material. In addition, the backing material and the facing materials must be uniformly attached to the transducer array.

In the design and construction of a CMET, we are interested in two properties: transducer *connectivity* and transducer *coupling*.

Transducer Connectivity

Because there are different ways of arranging the array elements for specific transducer production (Fig. 9), designers needed a way of easily expressing these various architectures. This organizational property is called *connectivity* and uses a pair of numbers to express the different material distributions. Connectivity refers to the continuity of each material pathway along each axis of the composite array.[5] The first number refers to the PZ material, and the second refers to the polymer. Thus, a 2-2 composite array has elements arranged to look like a stack of PZ-polymer sandwiches. The 2-2 designation means that both the PZ material and the polymer have two axes of connectivity. This is the typical organization of many linear, curved-linear, and phased arrays.

We are also interested in the one to three arrays that end up looking like a set of small, individual PZ elements surrounded on four sides by polymer. Each PZ “island” is surrounded by a polymer “sea.” In this architecture, the PZ material has only one axis of connectivity, whereas the polymer has three axes of connectivity (Fig. 9). This is the architecture of multielement, sequenced transducers with electronic focusing both along the array as well as along the thickness axis.

Transducer Coupling

Transducer coupling refers to the ability to transfer ultrasonic energy out of the transducer and into the tissues.[5] Should coupling decrease, transducer sensitivity on the receive side decreases along with the amount of ultrasound coupled out of the transducer into the tissues on the transmit side of events. Coupling can be improved in an array by using $\lambda/4$ layers of matching material that have an intermediate characteristic impedance value (Fig. 10). The intermediate values reduce the overall re-

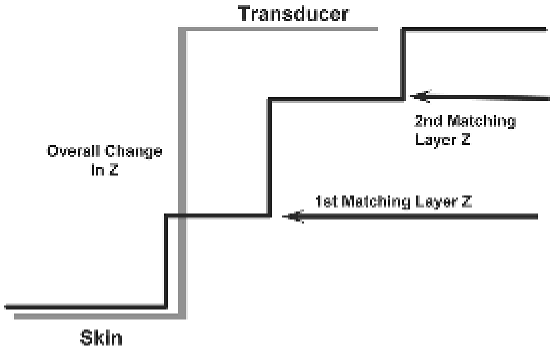

FIG. 10. Energy coupling into and out of the transducer depends on reducing the great impedance jump that exists between the soft tissues and the transducing elements. λ/4 layers with impedances less than the tissue-transducer interface smooth this transition.

flectivity of the PZ-layer interface. Typical scanhead design uses two of these layers, each with a different acoustical impedance but where the addition of both impedance values is less than the PZ material alone (Fig. 10).

Along with basic coupling efficiency, draining mechanical energy from the transducer directly affects the FBW of each array element. When the transducer is better able to couple the ultrasonic energy out of the array, the ultrasonic burst becomes shorter and the FBW gets larger.

Measurements That Reveal the Array-Element Condition

The ideal situation for a transducing array is to have each element identical to all the others and yet be functionally independent of one another. The task is to gather these identical transducing elements into an aperture configuration that produces a specific, electronically focused beam. Measurements that can reveal the array-element condition need to be exercised on each array element. What happens to this focusing, however, when the elements are no longer identical or not working at all?

An ideal list of tools and techniques to evaluate composite transducers can be rather large, employing measurements that are often difficult to perform in the field.[5] Laboratory measurements on CMETs reside in the following domains: (1) the time domain response, which would include the pulse shape and pulse length; (2) the frequency domain response, which would include the FBW and COF, a plot of the amplitude versus frequency spectrum, and electrical properties of the element as a function of frequency; and (3) the space domain response, which is the physical shape of the V-beam, obtained by special photography or detailed mapping of the acoustic field with a steel ball target or a piezoelectric microprobe.[5]

A smaller subset of these measurements, however, could easily reveal an essential transducer element condition without an unwieldy set of tools. An example of such a device is available.[10] A set of working parameters for such a device could include sensitivity (ability to detect the smaller echo signals), COF, FBW, pulse shape (pulse rise and decay times), pulse length, and measured capacitance of the electrical line and transducer together.

Transducer sensitivity expresses the ability of the transducer to respond to small echo signals. A reduced sensitivity means the transducing element cannot capture the smaller echo signals.

Transducer COF is a measure of the natural resonant frequency (NRF) of the transducer element. This frequency should be the same for each element in the whole transducer array. In a CMET, the polymer surrounding each transducing element increases individual element damping, which lowers an element's COF.

Transducer fractional bandwidth expresses the relative damping and coupling characteristic of each functioning element. The greater the damping and coupling energy out of the transducer, the shorter the echo signal and the greater the FBW.

Pulse shape is a consequence of the component waves present in an ultrasound burst. This measurement is a visual inspection of the burst waveform to locate the obvious presence of burst malformations that could change the FBW and the contribution each transducing element makes to overall axial resolution.

Pulse duration is a measurement that quickly indicates the individual contributions to overall axial resolution. This measurement of the pulse duration extends from the –20 dB beginning and ending points of the received pulse. The pulse duration is measured in nanoseconds (ns). The pulse duration has a direct effect on the system axial resolution and FBW.

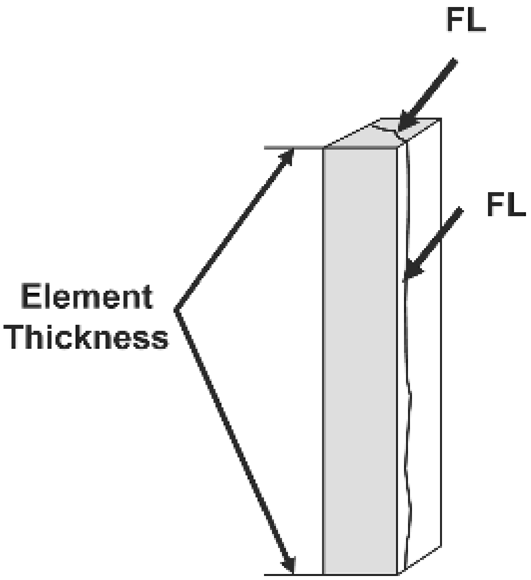

FIG. 11. A fractured element can act like two elements in contact. FL is the fracture line that creates two asymmetric transducing elements.

Element and cabling capacitance measurement is a rapid test of the electrical connection continuity of the coaxial cable, extending from the scanhead connector to the transducing element, including the ground and electrodes in contact with the PZ material.

Anticipating Transducer Problems

Based on an unscientific sampling of more than 3000 transducers from a wide range of clinical sites, approximately 25% of the CMETs currently in use have some form of structural, electrical, or acoustic performance compromise.[11] A major source of operational problems in the field is a traumatized scanhead, that is, an assembly that has been dropped or otherwise struck while in use or during transport within a clinical facility. Inside the injured scanhead, cracked transducing elements may still operate but not like two isolated elements (Fig. 11). Their interaction acoustically is likely to produce unexpected and unsuspected anomalies in operation.

Very often, the transducer elements are completely broken, along with a loss of electrical continuity. These are "dead" elements whose absence distorts the primary wavefront essential for beam formation and steering. The element response is very binary in this condition. The transducing element either works or does not.

Quality Assurance for the Ultrasound System

Quality assurance for the complete sonograph (scanhead and signal processor) can rest on a passive tool such as a TMP with a known set of targets available to test overall system performance. The testing protocol can include detail resolution (axial and lateral) (also known as the point spread function), contrast resolution, sensitivity, dynamic range, temporal resolution (frame rates, temporal filters, persistence, and compounding multiple-frame averaging). All of these tests, however, assume the scanhead to be working correctly. There is no easy way of moving from image quality assessment on a TMP to a detailed evaluation of the CMET. Making an element-by-element evaluation requires a different tool.

Quality Assurance for the CMET

It is important to understand that the terms *quality assurance* (QA), *quality control* (QC), and *preventative maintenance* (PM) are often interchanged but are not functionally the same. PM may include cleaning and inspection but often does not include detailed QA or QC testing. An original equipment manufacturer (OEM) may not move from an established PM program until the user complains about a reduction in image quality or the appearance of a functional failure.

In the process of developing, manufacturing, and using technology, two opportunities for quality assessment occur: (1) testing specific components of a technological ensemble such as a scanhead assembly during manufacturing and (2) testing an integrated subsystem or the wholly integrated system such as a complete sonograph in clinical use. Testing modular components or a whole system (a sonograph) represents a QA program. Thus, a QA program is a protocol of tests designed to ensure that a sonograph is working to specifications within its clinical setting. In contrast, a QC program focuses on ensuring that a sonograph and its

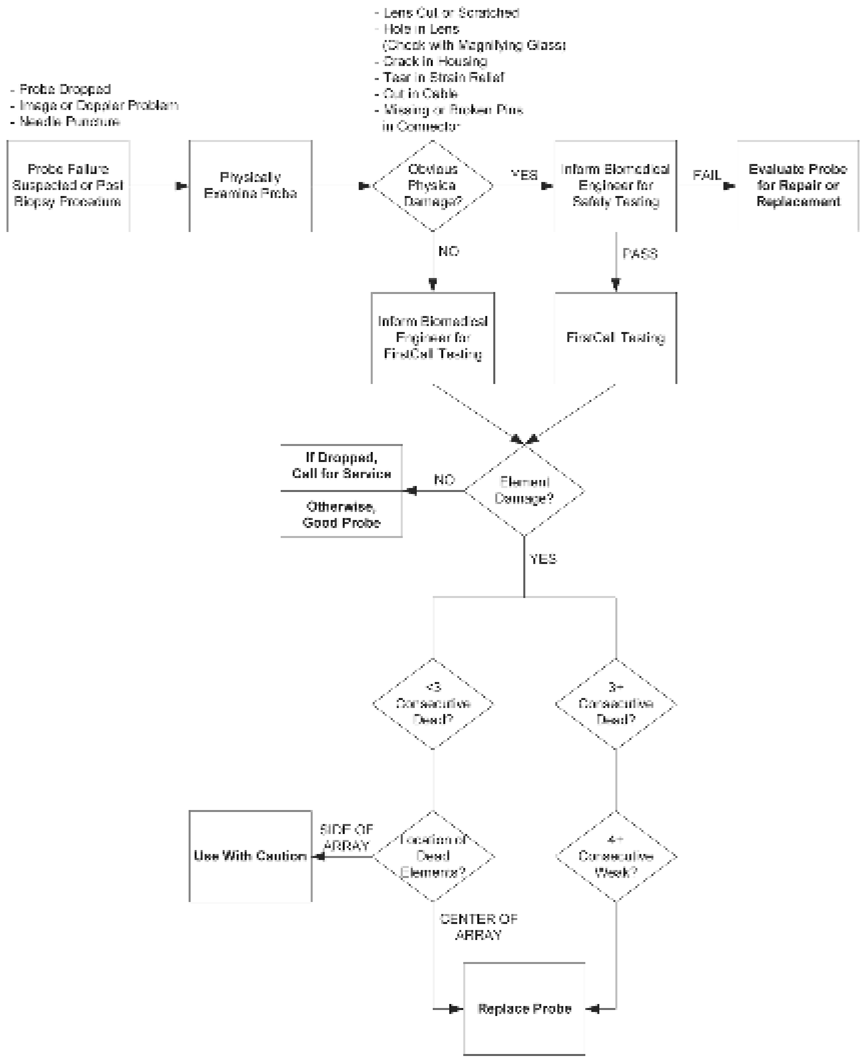

FIG. 12. A protocol for testing and evaluating the composite multielement transducer.

transducers meet manufacturing specifications. QC is a set of rules different from testing a system in a clinical setting, which is QA. The focus for this discussion is testing fully integrated CMETs that are separated from the sonograph but still part of an operating system.

Figure 12 depicts a flowchart that indicates when to call in a biomedical engineer to execute a detailed test of a suspected CMET scanhead using a multielement testing device such as the FirstCall2000™.[10] The branching points are all binary (yes or no, pass or fail, etc.).

Scanhead testing begins with a visual inspection of the transducer contact or wear surface. As the name implies, frequent use can wear or damage this surface, permitting caustic fluids, gels, or microorganisms admittance to the inner portions of the scanhead. A simple magnifying glass is needed for this inspection.

In the section on element damage, the acceptance/rejection criterion focuses on the number of elements damaged within the array. This criterion emerges from a set of experiments that tested image quality versus the number of failed elements.[11] For example, losing fewer than three elements does not seem to markedly affect gray-scale image quality. On the other hand, losing more than four elements can seriously degrade the image quality.[11]

Doppler experiments with various patterns of dead elements indicate that as few as two consecutive dead elements can lead to an underestimation of the maximum flow velocity, as well as introduce ambiguity concerning flow direction and flow organization.

Conclusion

Although the complexity of signal-processing architectures and scanheads has increased dramatically over the past two decades, our ability to test the advancing transducer designs has lagged behind these developments. As the diagnostic prowess of ultrasound continues to expand and as this technology continues to diffuse into more and more hands, the need for evidence-based quality assurance of these systems and their attendant transducers is becoming increasingly important.

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