Spectral Doppler Instrumentation

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In the first part of this series on Doppler ultrasound physics and instrumentation,[1] we discussed the application of the Doppler equation to the measurement of blood and cardiac tissue velocities. The purpose of this article is to describe the instrumentation principles of continuous- (CW) and pulsed-wave (PW) Doppler, referred to as spectral Doppler.

Instrument Design

Designs of CW- and PW-Doppler instruments are illustrated in Figures 1 and 2.[2,3] With CW Doppler, continuous electrical stimulation of piezoelectric elements occurs with a resultant continuously emitted ultrasound beam. The frequency of the emitted ultrasound wave is determined by the frequency of the stimulating electrical current. As we have previously described,[1] the propagating ultrasound wave undergoes a change in frequency (termed a Doppler shift) upon reflection from a moving target. The returning Doppler-shifted ultrasound wave induces “receiving” piezoelectric elements to resonate, resulting in an electrical signal whose frequency is then compared to the emitted ultrasound frequency. The difference between the emitted and reflected frequencies (the Doppler-shift frequency) is then calculated. A filter removes low-frequency high-amplitude signals originating from slow-moving reflectors (cardiac walls), leaving low-amplitude higher Doppler-shift frequencies (red blood cell movement). As both the transmitted and returning ultrasound waves contain multiple frequencies, there are multiple Doppler-shift frequencies. A mathematical algorithm termed fast Fourier transform (FFT) extracts frequency information from the returning signal. Sequential FFTs are performed to display the Doppler signal over time. Doppler-shift frequencies are converted to velocity information (according to the Doppler equation)[1] and displayed as a velocity spectrum (Figs. 1 and 2). The Doppler-shifted frequencies are also output as an audio signal, which may be heard during the clinical Doppler examination.

Pulsed-wave Doppler differs from CW Doppler in that piezoelectric elements are stimulated with a short electrical burst, thus creating an ultrasound pulse consisting of only a few cycles of ultrasound. Only one pulse is transmitted into tissue at a time, and during pulse propagation the transmitting elements act as signal receivers for the reflected ultrasound. A range gate is incorporated into the instrument, which represents the time during which the ultrasound machine “listens” to the returning echoes (see below). Echoes from multiple pulses are combined, with a sample-and-hold circuit allowing the signal to be built up sufficiently for accurate determination of Doppler-shift frequencies.

Locating the Origin of Echoes: Range Resolution

As ultrasound propagates through tissue, reflected ultrasound waves constantly return to the transducer. The ultrasound machine can

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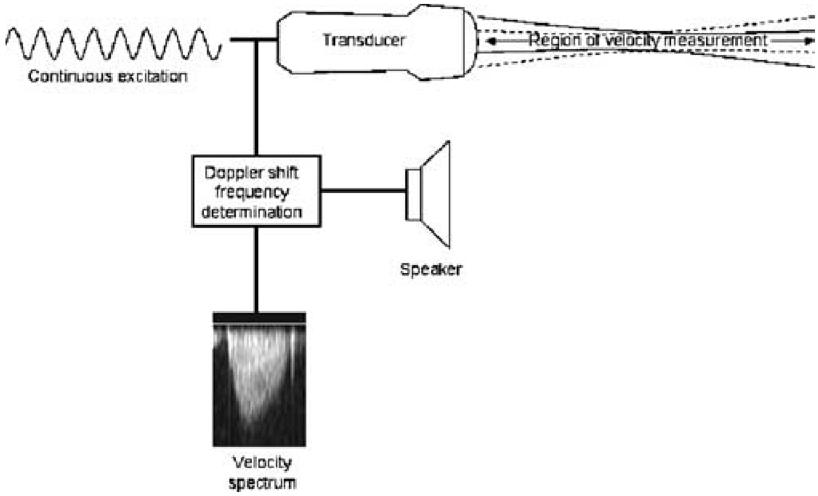

Figure 1. *A continuous-wave Doppler instrument. The dashed line represents the transmitted ultrasound beam, whereas the solid line represents the received ultrasound beam. Velocity is measured in the area of overlap of the transmitted and received beams.*

only determine the origin of an echo (range resolution) when one emitted pulse is allowed to travel at a time. Because the average propagation speed of ultrasound in soft tissue is known (1540 m/sec), the ultrasound determines the depth from which echoes originate, by "listening" at a specific time corresponding to the desired depth. Depth (d) is calculated according to the following equation:

$$d = ct/2$$

where c is ultrasound propagation speed, and t is the total pulse-echo travel time.

The range gate incorporated into PW-Doppler instruments only processes received echoes during a specific period of time, known as the gate length (Fig. 3). This time period corresponds to a region of interest referred to as the sample volume. The Doppler user positions the sample volume at the desired site of velocity measurement. Sample volume length (typically 1–5 mm) may be adjusted by the Doppler user and is determined not only by gate length, but also by the length of the propagating pulse. Because CW Doppler involves continuous emission of ultrasound, it cannot determine the origin of received echoes (range ambiguity). As a result, CW Doppler systems measure velocity over the entire region of overlap of the transmitted and received ultrasound beams.

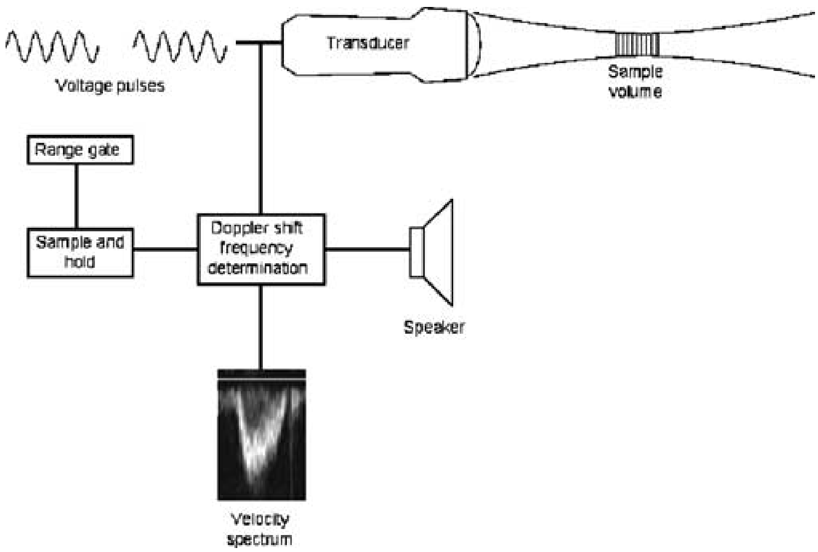

Figure 2. *A pulsed-wave Doppler instrument. Discrete voltage pulses produce similar ultrasound pulses. Information from multiple pulses is stored to derive the Doppler shift frequencies. The site of origin of Doppler frequency shifts is determined by the location of the sample volume.*

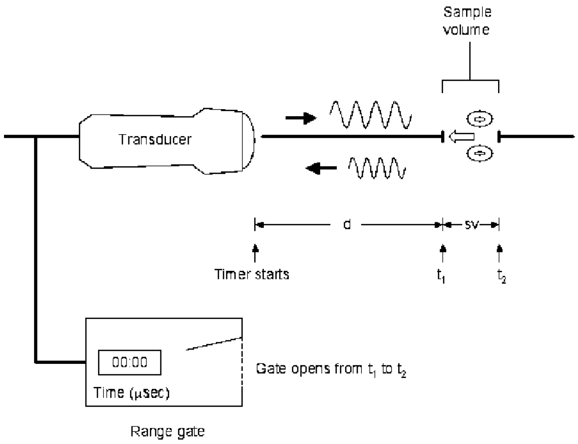

Figure 3. *Illustration of gate length. The timer starts when a pulse is emitted by the transducer. The range gate initially opens when the echoes originating from pulse-reflector interfaces at the proximal end of the sample volume have returned to the transducer (at time $t_1 = 2d/c$). The gate remains open during the time required for the pulse to traverse the sample volume and for the corresponding echoes to return to the transducer. The gate then closes (at time $t_2 = 2(d + sv)/c$); thus gate length extends from t_1 to t_2. c, propagation speed of ultrasound (1540 m/sec); d, depth of sample volume; sv, sample volume; t_1, time of opening of range gate; and t_2, time of closure of range gate.*

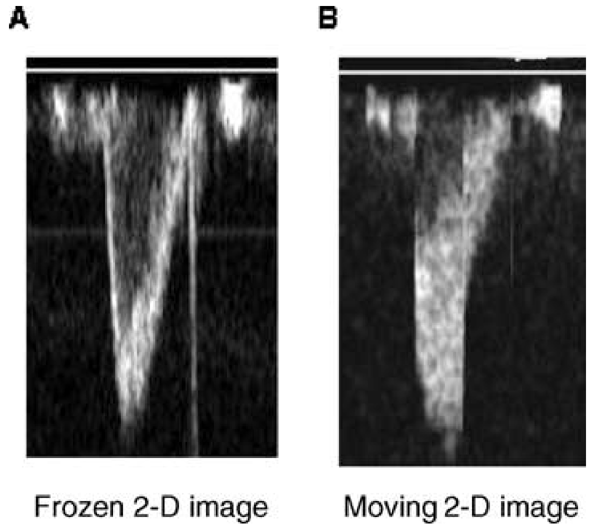

Figure 4. *The effect of simultaneous acquisition of real-time two-dimensional images and velocity spectra.* **A.** *A pulsed-wave Doppler velocity spectrum obtained from the left ventricular outflow tract (apical 5-chamber view) with a frozen two-dimensional image. The velocity spectrum shows much better delineation of velocities when the two-dimensional image is frozen.* **B.** *A pulsed-wave Doppler velocity spectrum obtained from the same location without freezing the two-dimensional image.*

Duplex Systems

The typical ultrasound machine is a duplex instrument capable of displaying both anatomic (gray-scale) and Doppler velocity data.[3] This allows the Doppler user to visualize correct positioning of the Doppler sample volume. The ultrasound machine cannot adequately perform both duties at the same time, and must switch between obtaining a gray-scale image and Doppler velocity spectra. As a result, the gray-scale image is displayed at a relatively low frame rate, and the velocity spectrum has a relatively poor resolution (Fig. 4). Thus, in order to display the highest quality velocity spectra, the gray-scale image should be "frozen" after positioning the sample volume.

In summary, we have discussed the design of CW- and PW-Doppler instruments, and their integration with two-dimensional gray-scale imaging. CW Doppler involves continuous emission of ultrasound and is therefore unable to localize resulting echoes (range ambiguity). With PW Doppler there is transmission of multiple discrete ultrasound pulses, and velocity information may be localized to a depth setting (range resolution).

In the next part of this series on Doppler ultrasound physics and instrumentation, the topic of signal aliasing and how it relates to Doppler ultrasound will be discussed.

References

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