Whitepaper

High Information Rate Volumetric Ultrasound Imaging

ACUSON SC2000 Volume Imaging Ultrasound System

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Abstract

Real-time volumetric imaging, a relatively new clinical application in ultrasound, is currently limited by the information rate of the ultrasound imaging system. Recent advances in integrated circuit technology and significant increases in computation and processing power make it feasible today to build ultrasound systems with significantly higher information rates. This paper will describe the vital attributes of the ACUSON SC2000™ volume imaging ultrasound system, a high information rate ultrasound platform that is designed and built to enable new clinical applications and full volume, real-time volumetric imaging.

Introduction

One of the fundamental attributes that makes ultrasound unique among medical imaging modalities is its being **real-time.** This is a tremendous advantage over other imaging modalities like CT or MRI, and is particularly important in clinical applications where temporal information, accuracy, or resolution is as critical as spatial information, accuracy or resolution. Examples of echo applications where temporal information is critical include imaging cardiac wall motion and blood flow and in monitoring cardiac procedures such as valve replacement and ablation. The real-time nature of ultrasound also enables clinicians to have direct interactive contact with the patient during scanning.

The key performance measure of real-time imaging systems is the **information rate**. This simple measure unifies many of the well known image quality determinants such as temporal resolution, field of view, penetration, detail resolution and contrast resolution. In fact, the information rate of an imaging system defines the upper boundary for achievable image quality and exam efficiency, and therefore drives the **diagnostic confidence** and **speed of workflow**. Given this upper boundary, performance in any of the image quality parameters can be improved by trading off performance in others through various controls and presets provided to the user. Operators of ultrasound imaging systems frequently use these means such as frequency, image width, line density, etc., to select the trade-offs that are correct for the particular clinical application or patient. For example, imaging frequency is increased to improve detail resolution, trading off penetration and temporal resolution. The image width or display depth can be reduced to improve temporal resolution, trading off field of view, and so on.

As new clinical applications and imaging techniques emerge, the information rate of existing platforms has become the bottleneck. Today, real-time volumetric imaging is the most challenging application of all as expanding the field of view from a 2D slice to a full 3D volume is not possible without significant trade-offs in temporal, detail, and contrast resolution and penetration, unless the system information rate is increased dramatically. In addition, the performance of many specialized imaging techniques such as spatial and frequency compounding, elasticity imaging and contrast agent imaging are also limited by the system information rate. These techniques require multiple pulse/echo events per line of sight to gather information on parameters such as angle or frequency dependence of the tissue response, nonlinearity or stiffness of tissue and contrast. Therefore, the limited information rate imposes trade-offs in field of view, temporal resolution or image quality.

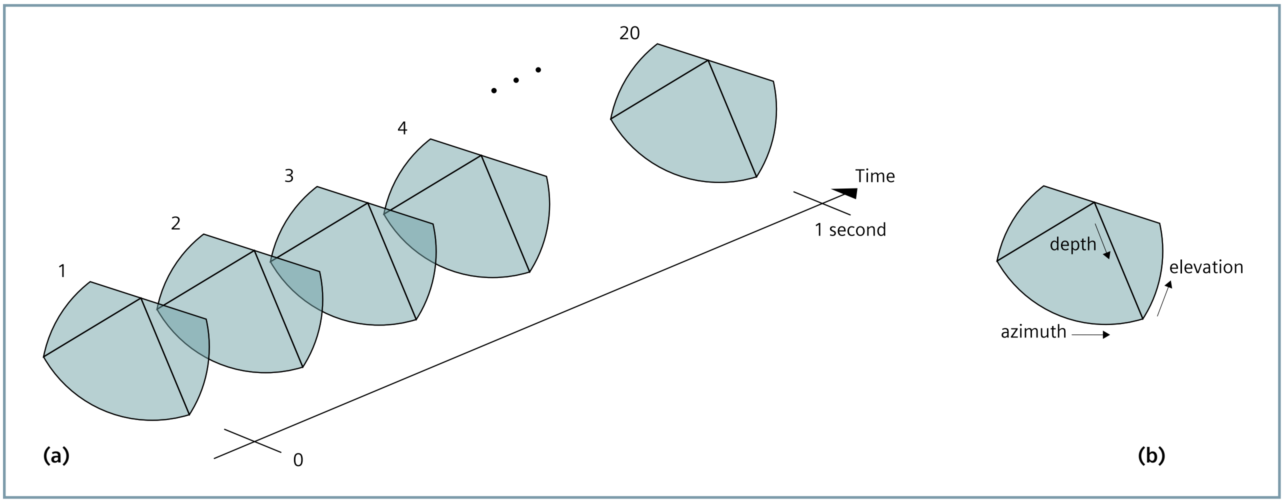

Figure 1. ***(a)*** *Volume rate is given by the number of volume images formed per second.* ***(b)*** *Volume size is given by the image width in lateral dimensions azimuth and elevation, and the penetration depth.*

Information Rate

To extend this discussion, information rate needs to be defined and the contributing properties well understood. For real-time volume imaging engines, the *information rate*, or information per second, is given by the *information per volume times the temporal resolution.*

$$\textit{Information Rate} = \textit{Information / Volume} \times \textit{Temporal resolution}$$

Temporal resolution is the ability to detect motion and is given by the volume rate, or the number of volumes formed per second (frame rate or frames/sec for 2D imaging). See **Figure 1(a)** for a graphical description of volume rate.

The *Information per Volume* in turn is given by the V*olume Size* times the *Information Density*, or the information per unit volume (e.g., per cm^3).

$$\textit{Information / Volume} = \textit{Volume Size} \times \textit{Information Density}$$

Volume size is given by the image width in the two lateral axes, azimuth and elevation, and the penetration, the deepest depth with information **(Fig 1.b)**.

$$\textit{Volume Size} = \textit{Width in Azimuth} \times \textit{Width in Elevation} \times \textit{Penetration}$$

Information Density is a measure of detectability of tissue echogenicity variations. It is directly proportional to the detail resolution and contrast resolution and is given by

$$\textit{Information Density} = \textit{Detail resolution} \times \textit{Contrast resolution} = \frac{\textit{CNR}^2}{\textit{Resolution cell size}}$$

Detail resolution determines the detectability of closely spaced acoustic inhomogeneities. It is inversely proportional to the resolution cell size or the volume of the point spread function.

Contrast resolution, which should not be confused with image contrast, determines the detectability of resolvable structures and is a measure of how low the acoustic noise levels are[1]. The contrast resolution measure is the Contrast to Noise Ratio (CNR).

$$CNR = \frac{\bar{I}}{\sigma}$$

Where $\bar{I}$ is object's average brightness representing the average echogenicity, or the information. We assume unity $\bar{I}$ to keep the measure object independent. σ is the point-wise standard deviation of acoustic noise. For simplicity we here assume that the dynamic range of the platform is sufficient to prevent saturation or clipping, and the quantization is not a dominant source of noise.

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[1] *There are two types of acoustic noise, speckle and clutter, that prevent detection of otherwise resolvable structures. Reducing speckle or clutter increases contrast resolution and therefore information.* ***Speckle*** *is the acoustic noise generated by unresolvable micro structures. Due to the coherent or phase-sensitive nature of ultrasound beamformation, echo from multiple scatterers within each resolution cell volume interfere constructively, i.e., in-phase, and destructively, i.e., out-of-phase, and create a random pattern called speckle. Speckle is an additive noise for B-mode. When an object has nine or more unresolvable scatterers within a resolution cell volume, it generates fully developed speckle. Speckle is a formidable challenge to detectability of otherwise resolvable structures. Techniques like compounding that reduce speckle variance are critical to the detectability of resolvable structures.* ***Clutter*** *is the acoustic noise resulting from scattering from off-axis resolvable and unresolvable structures. It prevents the detectability of on-axis resolvable structures. Second harmonic imaging is the most effective technique used today to reduce clutter.*

To summarize, the information rate is directly proportional to detail, contrast and temporal resolution (volume or frame rate) and field of view (volume or frame size). The information rate unifies these well known information parameters into one extremely valuable measure for real-time imaging systems. To improve any one of the information parameters without a trade-off in others requires a platform with higher information rate.

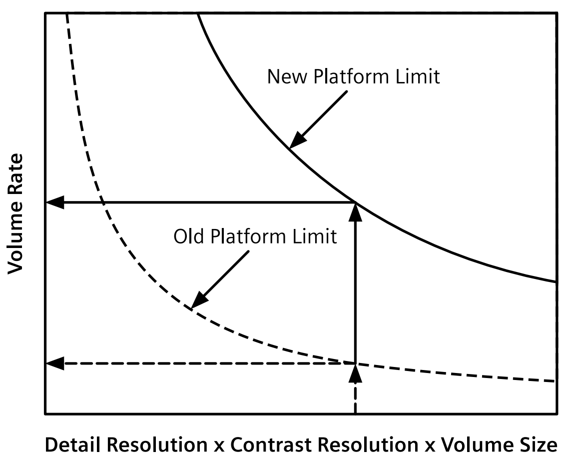

Figure 2. *Platform's information rate limits information parameters.*

This point is illustrated in **Figure 2**. The dashed and the solid curves show the maximum achievable volume rate as a function of the combined parameter (detail resolution × contrast resolution × volume size), respectively for an older platform and a new platform with much higher information rate. Note the inverse relationship between the volume rate and the rest of the parameters. For a given target detail resolution such as, contrast resolution and volume size (the vertical arrows), the only way to increase volume rate is to increase the information rate. Otherwise, performance in one or more of the three combined parameters is compromised.

The very same inverse relationship exists for any one or two of the parameters vs. the rest of the parameters combined, e.g., contrast resolution vs. *detail resolution × volume rate × volume size;* volume size vs. *detail resolution × contrast resolution × volume rate;* or *volume rate × volume size* vs. *detail resolution × contrast resolution.*

Furthermore, in addition to the potential information rate limitation of the system, the body may impose limitations on one or more of the parameters as well. For example, in echocardiography, detail resolution is limited by the acoustic window size between the ribs which determines the maximum aperture size, and by the penetration requirements of the application which determine the imaging frequency. For echocardiography, an increase in information rate directly translates into improvements in volume rate, volume size and/or contrast resolution.

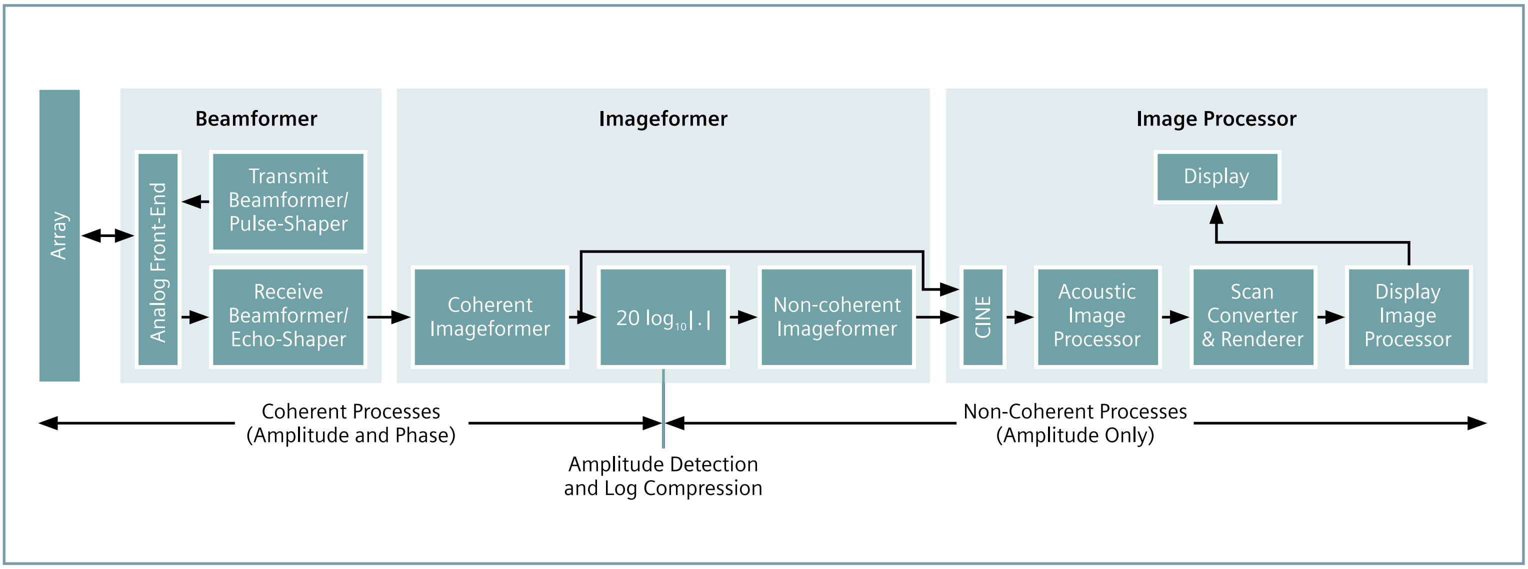

Figure 3. *Imaging Engine Conceptual Block Diagram.*

High Information Rate Imaging Systems For Real-Time 3D Imaging

The imaging engines of today's 2D ultrasound systems do not have sufficient information rate to achieve full volume real-time 3D imaging and perform partial volume sampling of the target organ. The ACUSON SC2000 system introduced an imaging engine with unparalleled information rates to enable full volume volumetric imaging in real-time.

The conceptual block diagram in **Figure 3** shows the major components of a high-end imaging engine, namely beamformer (front-end), imageformer and image processor (back-end). The front-end drives the transducer and acquires data in spatial, temporal and parameter domains. The imageformer synthesizes and compounds spatial, temporal and parameter domain data provided by the front-end into images. The back-end enhances the images, converts them from acoustic scan grids to display (Cartesian) grids, then renders and displays them.

Real-time volume imaging requires highly sensitive two dimensional matrix arrays. These arrays, by necessity, have thousands of elements to electronically steer and focus in both azimuth and elevation. To reduce the cable count, some front-end functionality is typically moved into the transducer handle. The electronics in the transducer handle is considered a part of the imaging engine.

The two most important attributes of a high information rate imaging engine are its front-end parallel beamformation capability, and coherent imageformation capability. The ACUSON SC2000 system has a volumetric imaging architecture that can sustain very high information rates from front to back. This includes a real-time parallel beamformation capability in the front-end with up to 64 parallel beams, and the proprietary Coherent Volume Formation™ technology, a 3D coherent imageformation technology that can form 3D images at up to 160 M voxels per second.

Parallel Beamformation

The front-end acquires three types of data, namely spatial, temporal and parameter domain. The spatial domain data provides structural information in up to three spatial dimensions. The temporal domain data provides tissue motion and blood flow information. The parameter domain data provides information on the angle/frequency dependence of tissue response, or on the acoustic properties such as nonlinearity, stiffness, etc.

To acquire data, the transmit beamformer of the front-end subsystem transmits specially shaped and timed pulses into the body thousands of times per second. The receive beamformer then generates multiple beams through parallel and real-time processing of echo received in response to each transmitted pulse. The number of receive beams the receive beamformer can generate in parallel determines the maximum information rate the imaging system can achieve.

The finite speed of sound in tissue (~1,540 m/s) imposes a physical limit on the maximum number of pulses the front-end can fire per second. It takes hundreds of microseconds for a round trip pulse to reach the deepest depth of interest and then to propagate back to the acoustic array. To prevent ambiguity of echoes, the next pulse is held until all return echo from the previous pulse is received. For example, for a 16 cm depth of interest, the round-trip propagation time is ~200 microseconds which limits the number of pulses to ~5,000 per second.

While the speed of sound limits the maximum pulse rate, the size of the volume, target volume rate and lateral resolution determines the total number of beams needed per second. For example, full volume (90° × 90°) transthoracic echo imaging at a target volume rate of 25 volumes/sec requires forming 100,000 to 200,000 beams per second, depending on the lateral resolution. To form this many beams with only 5,000 transmit pulses, the front-end needs to form 20 to 40 beams in parallel for each transmit pulse. Real-time imaging of motion, flow or parameters like nonlinear response require even higher parallel beam counts as they need a higher number of pulse-echo events for the same volume size.

The ACUSON SC2000 imaging engine is capable of forming up to 64 beams in parallel. In comparison, its predecessor, the ACUSON Sequoia™ ultrasound system is able to form up to 4 beams in parallel. This amounts to an increase in information acquisition rate by a factor of 16.

Coherent Volume Formation

The imageformer receives the multi-domain, multi-dimensional data acquired by the front-end in the form of beams. It then filters, synthesizes and compounds the beams into high quality images of one or more parameters of interest.

The amplitude detection and log compression stage of the imageformer separates it into two important subsystems, namely the coherent imageformer, for the phase sensitive processing of analytic signals, and the non-coherent imageformer, for the phase insensitive processing of log-compressed amplitude (video) signals.

The coherent imageformer was first introduced on the ACUSON Sequoia platform in 1996 to enable high quality dual beam operation and to preserve inter-pixel phase information in 2D. This system was able to provide twice the information in half the time, a four-fold increase in information rate as compared to the other high-end ultrasound imaging systems then available in the market.

The coherent imageformer of the ACUSON SC2000 system is specially designed for Coherent Volume Formation (CVF), an advanced 3D coherent image formation technology. The CVF technology aligns the phase of the beams generated by the receive beamformer and applies coherent or phase-sensitive processing across phase-aligned beams. This phase-sensitive processing plays two important roles. First, it captures the inter-voxel phase information before it is discarded by the amplitude detection stage of the imageformer. This allows the imaging system to preserve information and thus sustain the high information rate. Secondly, it is key for high quality multibeam operation with up to 64 parallel beams and programmable beam distribution in azimuth and elevation. This is achieved through retrospective transmit focusing, a CVF capability. The coherent imageformer is a critical component of high information rate, high image quality imaging and complements the massive parallel beamformation capability of the front-end subsystem.

The imageformer of the ACUSON SC2000 system can process up to 160 M voxel per second. This translates into an information processing rate increase of sixteen-fold compared to the ACUSON Sequoia system's 10 M pixel per second processing rate.

The images in **Figure 4** demonstrate the benefits of Coherent Volume Formation. **Figure 4(a)** shows a full 90° × 90° volume acquired at 20 volumes/sec without the conventional gated acquisition and stitching data from multiple heartbeats. A cut-plane through the middle of the volume allows visualization into the chambers of the heart. Achieving this level of temporal resolution at full volume size requires much higher beamformer processing bandwidth than a 2D platform can sustain.

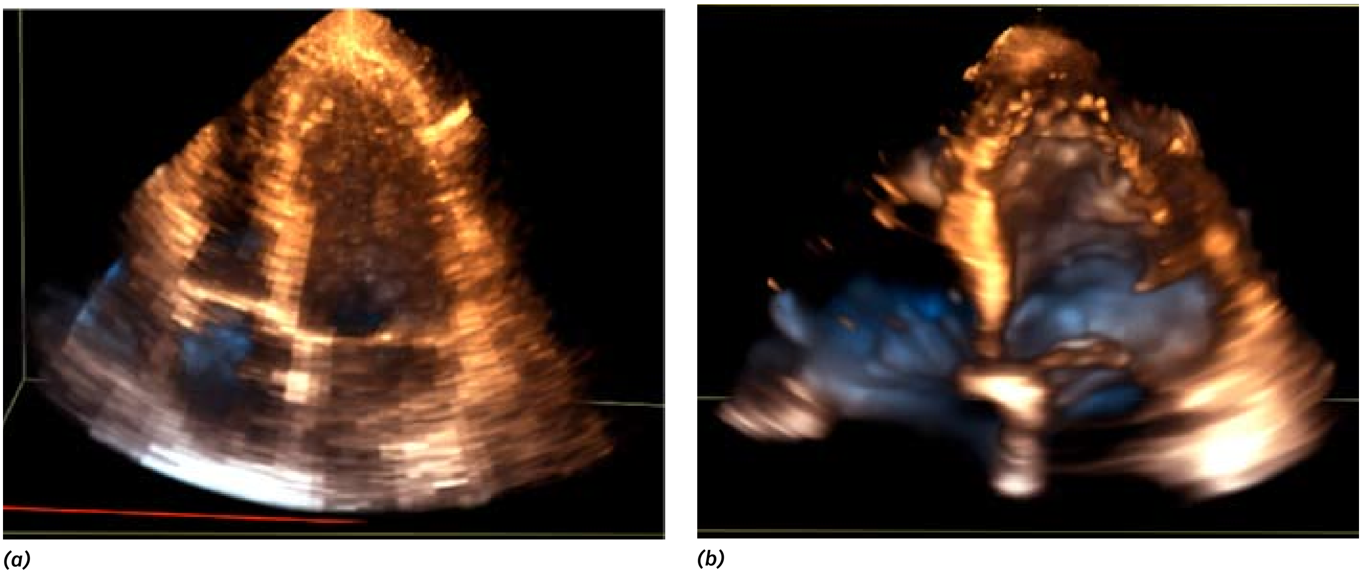

Figure 4. ***(a)*** *Massive parallel beamformation capability is necessary for real-time volumetric imaging but it is not sufficient.* ***(b)*** *For image quality, and lossless amplitude detection it has to be complemented with image formation technology.*

Note that clinical images are presented to illustrate technical concepts and are not indicative of system image quality.

It also shows that increasing the beamformer processing bandwidth alone is not sufficient for high quality real-time 3D imaging due to artifacts inherent to multibeam operation and the loss of inter-voxel phase information through the amplitude detection process. **Figure 4(b)** combines the benefits of massive parallel beamformation capability of the front-end and Coherent Volume Formation capability of the imageformer.

Conclusion

The greatest practical differentiator of ultrasound is its real-time imaging capability. The information rate of existing platforms, originally designed for real-time 2D imaging, have become insufficient for emerging new applications such as real-time volumetric imaging. On these platforms, a full volume cardiac image is formed in a repeated progression stitching multiple sub-volumes acquired over multiple heart cycles and then re-animating the composite volume. This leads to loss of information on arrhythmic cardiac motion. In addition, discontinuities at the stitch boundaries limit the diagnostic utility of the images. To prevent stitch boundary artifacts, the patient has to hold his/her breath, adversely affecting the workflow, or rendering it impossible as in the case of stress echo.

The recently introduced ACUSON SC2000 platform acquires data, forms and processes images at significantly higher rates than the existing platforms. Its front-end is capable of forming up to 64 beams in parallel in real-time. The imageformer of the ACUSON SC2000 system supports proprietary Coherent Volume Formation technology, a 3D coherent imageformation technology with processing up to 160 M voxels per second. These increases in information rate enable the ACUSON SC2000 system to achieve full volume, real-time volumetric imaging continuously throughout the study and obviate the need for breath holding or the contra-indications for use from arrhythmias.

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