Advances in Ultrasound Imaging Architecture: Educational Overview—2021

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Abstract

Technological and engineering methods used in ultrasound image creation have evolved significantly over the past two decades. Conventional imaging architecture is characterized by inherent data loss and constraints on temporal resolution which limit not only image quality and uniformity but preclude the development of novel real-time diagnostic modalities. Advances in contemporary imaging architecture overcome these constraints by integrating new hardware and software capabilities into the ultrasound imaging chain. This paper presents an overview of these new engineering pillars and contrasts them to the conventional architectural design used in the creation of diagnostic ultrasound modalities.

Introduction

The process by which ultrasound images are created – the *image creation chain* - as taught in sonography educational programs has remained virtually unchanged for over thirty years. However, the reality is that significant advances in basic engineering and technological aspects of this process have changed forever the fundamental principles and tenets that are included as part of traditional SPI curricula. As always, it is imperative that users of all technology-based medical imaging modalities understand the physical and technological underpinnings of their tools so that appropriate and accurate clinical interpretations can be rendered. And while the principles of acoustic physics remain just that, immutable physical axioms, the engineering design and technological pillars incorporated into contemporary sonographic imaging platforms has undergone a sea change over the past several decades.

System Architecture – General Definitions

When discussing any sophisticated electronic, computer-based device, the term *architecture* refers to the complex and carefully designed conceptual and logical organizational structure of the system. It consists of the building blocks that underpin all of the system's operations, functions, and output. *Architectural design* consists of specific hardware and software components and the interrelationships between them that enable the system to perform effectively in generating a predictable, desired output.[1] A *platform* is the physical location where these architectural components reside and where its programs, processes, and applications can perform their expected functions. An ultrasound imaging system, affectionately called an *ultrasound machine* by generations of clinical users is, then, more accurately called an *ultrasound imaging platform*. Within the physical confines of this platform reside all the hardware, software, firmware, electronic circuitry, and other components that are carefully engineered to work together to generate and display all traditional, emerging, and potential future sonographic modalities.

Ultrasound Imaging Architecture – Engineering Pillars

Architecture specific to next-generation ultrasound imaging platforms is centered on four engineering pillars:

- Virtual-beamforming
- Big data
- Enhanced digital signal processing (eDSP)
- Bit-by-bit frame creation

Virtual Beamforming

Conventional ultrasound imaging systems rely on careful control of the geometric and acoustic characteristics of the transmit beam to yield high quality images. A physically narrowed ultrasound beam ultimately produces images with better spatial resolution at the level of focus. Conventional focusing is accomplished by using timing delays in varying and creative ways to the multiple piezoelectric elements arrayed in the transducer housing. (Figure 1a) These delays can be applied to either (or both) transmit and receive sides of piezoelectric transformation. Over the decades, as technological capabilities have improved, console knobs have given operators some control over beam focusing. In response to focal control manipulation, single or multiple depths may be selected to improve spatial resolution at the operator-determined level(s). The tradeoff to this method of image creation has always been increased individual frame creation time and a resultant reduction in displayed frame rate which, of course, diminishes temporal resolution. More focal zones yield better spatial resolution, however; temporal resolution is degraded proportionately.

The introduction of virtual beamforming methods has broken through this imaging constraint. As discussed below, enormous amounts of data are received at the transducer face after the ultrasound beam physically interacts with human soft tissue. This *acoustic data set*, after being converted into digital radiofrequency (RF) signals, can be recursively processed to apply delays which can focus individual data points in both transmit and receive modes for each received data set. Software algorithms are used to virtually focus the beam. (Figure 2a) The end result is that every pixel in every image frame is focused throughout the field of view without operator interaction and without attendant loss of temporal resolution. Another advantage of virtual beamforming is the ability to use larger transmit insonation regions for creating acoustic data sets. Various proprietary methods exist and include firing multiple transducer elements simultaneously to create larger acoustic zones, or mini-plane waves, and firing all elements simultaneously to create full plane waves. Retrospective software processing of these larger received acoustic data sets also helps overcome other well-known image quality constraints imposed by acoustic physics, i.e., beam divergence, beam breakage, and lobe artifacts.[2,3] Virtual beamforming provides numerous and obvious benefits in clinical imaging. These include: [4,5]

- Dramatically improved spatial resolution (axial, lateral, elevational) throughout the field of view (Figure 3)
- Full focusing in every frame throughout the field of view without need for operator interaction
- Improved image quality at depth
- Ability to use higher frequencies for deeper imaging
- Reduced imaging artifacts (side lobes, section thickness, beam breakage)

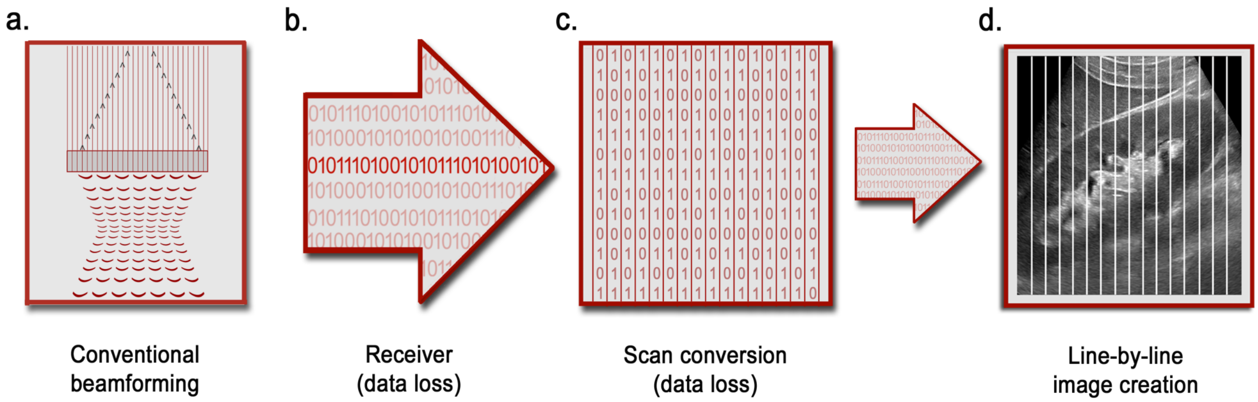


Figure 1: Conventional image creation chain architecture

Conventional beamforming methods (a) are used to create and acquire an acoustic data set which is sent into a receiver where approximately 90% of the data is truncated (b). Conversion and compression of receiver data into imaging data within the scan converter results in additional data loss (c). Each image frame is assembled using a fraction of the original data set in a line-by-line manner which places significant temporal constraints on image formation (d).

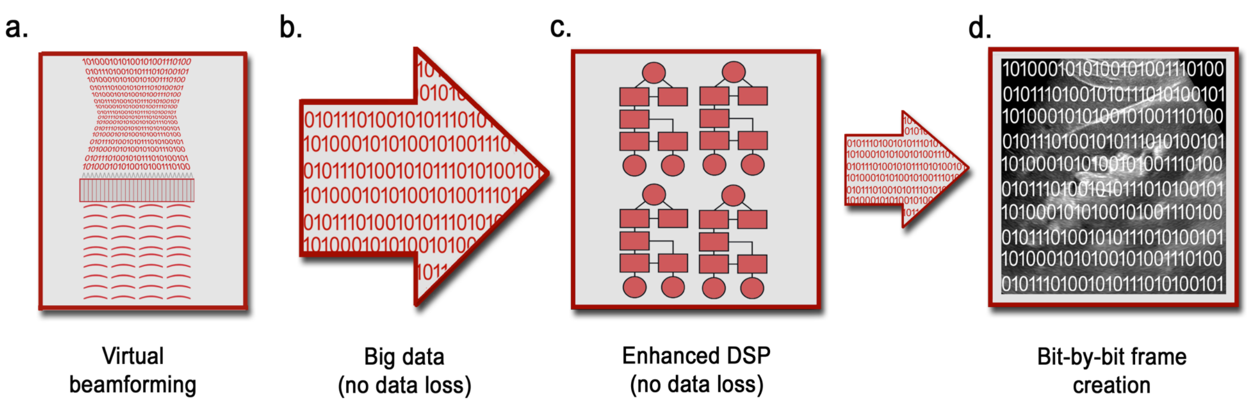


Figure 2: Advanced image chain architecture

Virtual beamforming applies software algorithms to the acquired acoustic data set to synthetically focus image on both transmit and receive (a). The large acoustic data sets, which are captured and stored as big data with virtually no data loss (b), are sent on for enhanced digital signal processing (c). Application of these processing algorithms permits bit-by-bit frame creation (d) with no appreciable diminution of temporal resolution and the ability to generate novel ultrasound applications.

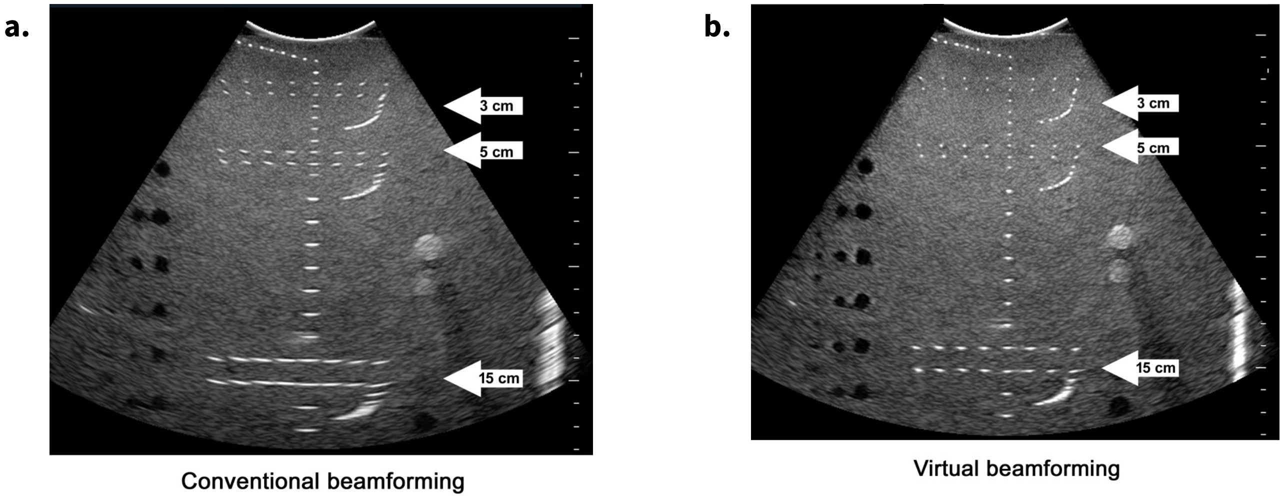


Figure 3: Virtual beamforming — improved spatial resolution

Comparison of *axial and lateral resolution* in a soft tissue pin phantom between conventional (a) and virtual (b) beamforming methods. Significant improvement is noted in both spatial dimensions at 3, 5, and 15 cm using virtual beamforming. Lateral splaying at 15 cm is expected in both images due to ultrasound beam divergence, however, it is noticeably reduced with virtual beamforming. Note is also made of the finer speckle pattern present in the virtual beamforming image (b) compared with the coarser appearance on the conventional image (a).

Big Data: Acoustic Acquisition and Transfer

The *image creation chain* begins, as always, with the predictable interactions produced when high frequency acoustic energy (ultrasound) interacts with human soft tissue. The energy emitted from the transducer (*transmit*) passes into the tissue being examined and predictable physical phenomena occur. Many of these interactions send altered bits of acoustic energy back to the transducer (*acoustic data set*) which are rapidly converted back into electrical signals by the piezoelectric crystals in the transducer (*receive*). These miniscule bits of electricity are then converted into digital signals, also called radiofrequency (RF) signals - the raw data used in all subsequent analytic and processing operations in the image creation chain.

Physical interactions that yield data useful in image creation and advanced modality displays include: specular reflection, non-specular reflection, attenuation, particle displacement, backscatter, Rayleigh scattering, and speckle production. Conventional ultrasound imaging architecture sends the received acoustic information to a receiver where, as the intended result of its multiple functions, truncates the data set. The compressed data is then sent to a scan converter where additional data loss occurs prior to the line-by-line creation of each image frame. (Figure 1b, 1c, 1d) The net result is a loss of nearly 90% of the information contained within the initial received acoustic data set creating significant constraints on improved sonographic image quality and the creation of novel diagnostic modalities.

Virtual beamforming methods generate enormous amounts of acoustic information as a result of the larger *transmit* insonation zones employed. The magnitude of individual data points *received* at the transducer and the range of acoustic characteristics attached to each individual data point number in the trillions, a range too large and complex to be acquired, transferred, processed, and analyzed by conventional ultrasound system architecture. The ability to do this requires hardware components capable of handling enormous amounts of discrete, unique raw data points at rates approaching the speed of light. This is sometimes referred to as *acoustic currency*. Use of enhanced central processing units, graphics processing units, and the integration of state-of-the-art microchips such as high-speed, high-capacity integrated circuits and field-programmable gated array (FPGA) chips make this possible. The acquisition, transfer, and processing, of these enormous data sets are generically referred to as "big data". (Figure 2b).

Big data methods are employed in virtually every discipline where enormous amounts of digital information must be analyzed to yield a desired outcome. Examples include: economics and financial markets, electronic health records, national intelligence activities, retail business tracking, NASA simulations, collection and analysis of astronomical data, decoding of the human genome, and countless other applications.[6] Ultrasound imaging architecture has joined the family by incorporating big data capabilities into the imaging chain.

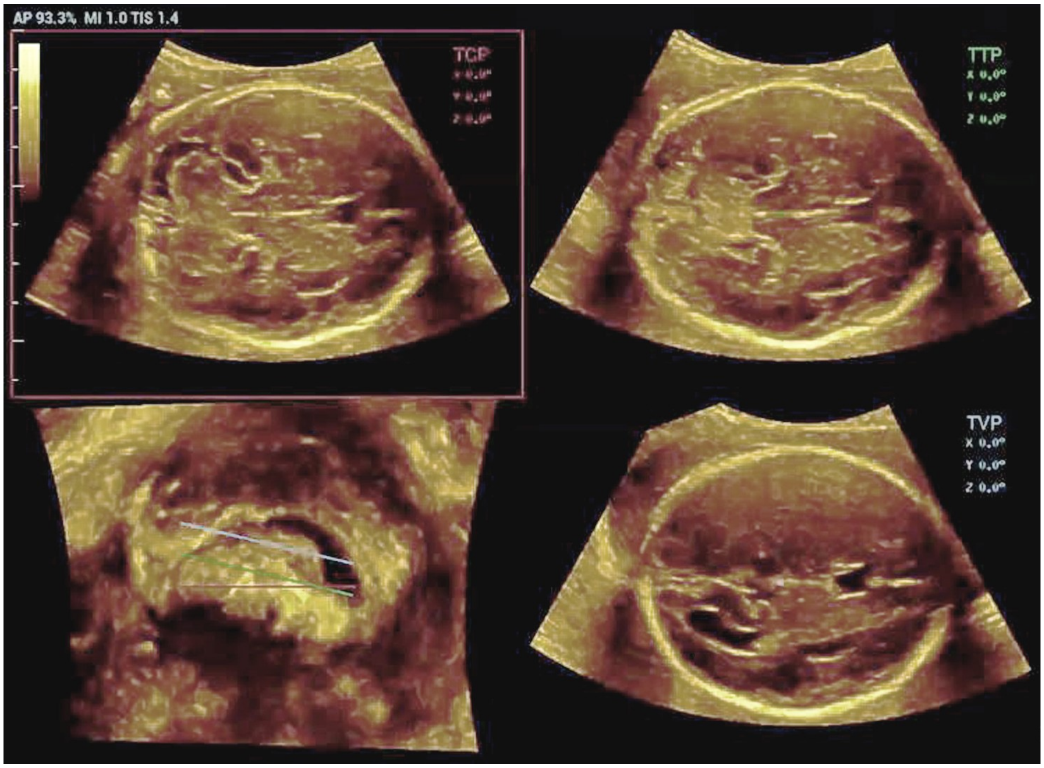
There are four basic elements characterizing big data as it relates to ultrasound imaging: [7]

- **Volume**: the trillions of discrete data points contained within the *received* acoustic data set created at each *transmit* cycle. After acquisition, this enormous received data set must be transferred *in toto* along the image creation chain.
- **Velocity**: the ability to rapidly transfer vast volumes of complex data from one point to the next in the image creation chain and to perform billions of calculations on each data set in real-time.
- **Variety**: the enormous variation in quality and acoustic characteristics associated with each data point present in the acoustic data set. Use of broader transmit bandwidths results in a broader receive bandwidth and a wider variety of data points.
- **Veracity**: the ability to maintain integrity and improve quality of acoustic information encoded on each data point. In conventional ultrasound imaging systems, receiver functions modify and truncate much of the received data placing constraints on sonographic capabilities and clinical applications.

The magnitude of acoustic information made available by big data not only permits improved image quality across all conventional modalities, it also opens the door for the creation of new and previously technically untenable applications. Big data is especially suitable for the integration of artificial intelligence (AI) and deep machine learning capabilities into the imaging chain. (Figure 4) These methods provide for improved image acquisition, real-time assessment of image quality, objective detection and diagnosis of disease, and optimizing clinical examination workflow.[8] Some specific benefits of big data in conventional diagnostic ultrasound performance include:

- Improved contrast resolution in two-dimensional gray scale imaging (Figures 5, 6)
- Improved spatial and contrast resolution in contrast-enhanced ultrasound (CEUS) imaging
- Quantification of existing modalities. i.e., contrast-enhanced ultrasound, shear wave and ARFI elastography (*sonobiometrics*)

a.



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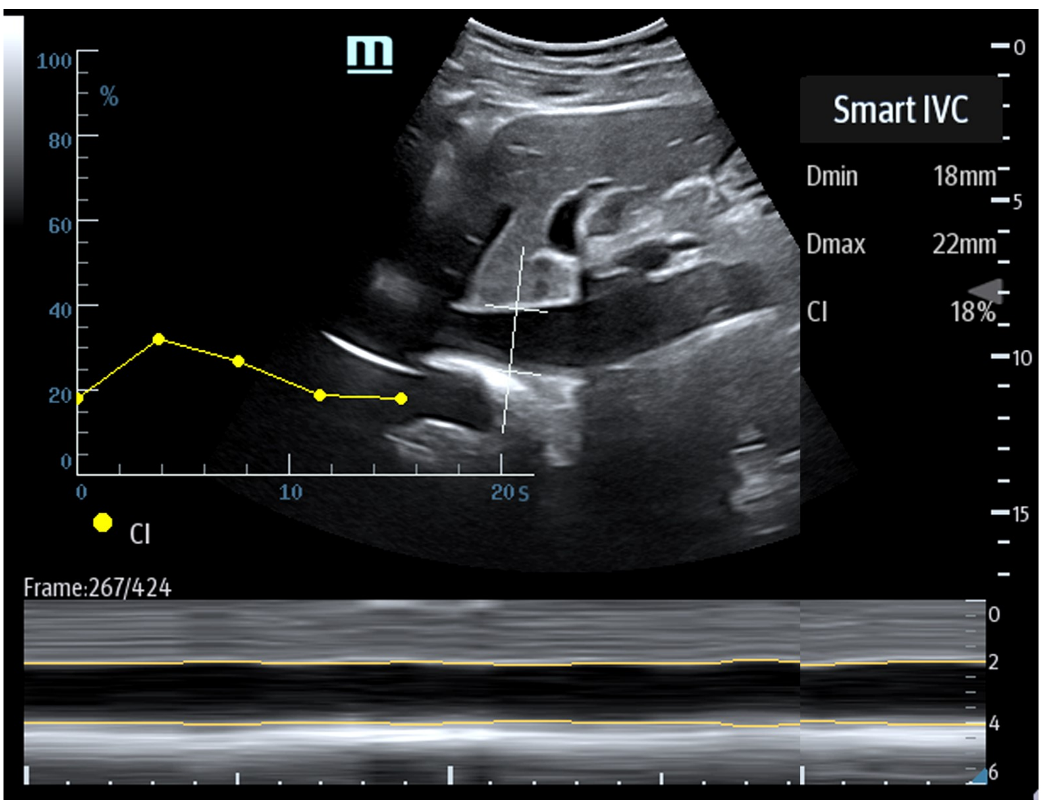

Figure 4: Examples of artificial intelligence applications

a. *Multiplanar reconstruction* of fetal head using a 3D volumetric data set and machine learning.

b. *Automated dynamic IVC measurements* used in volume status assessment and application of fluid therapy.

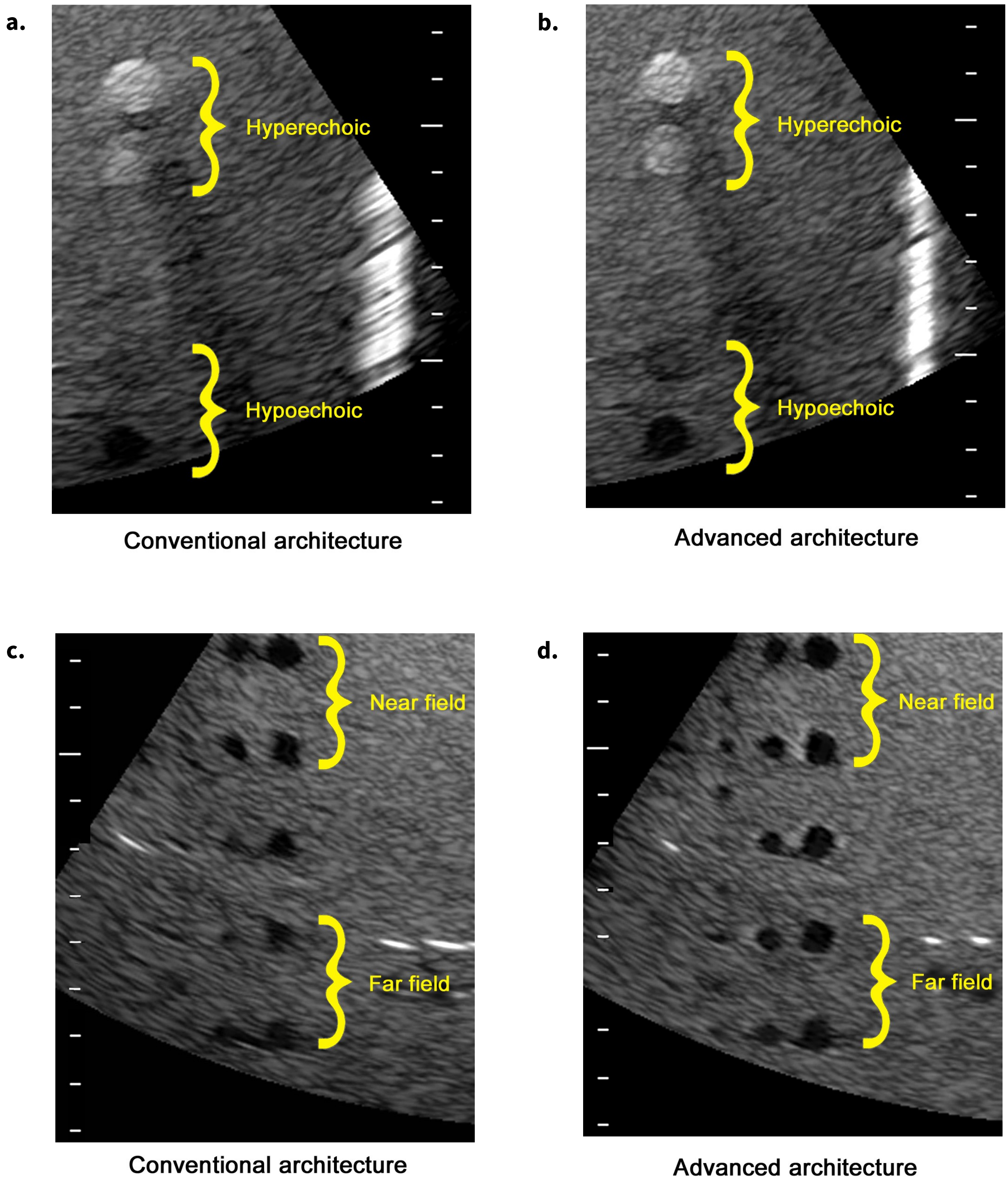

Figure 5: Big data with virtual beamforming — improved contrast resolution

Comparison of *contrast resolution* in a soft tissue phantom between conventional and advanced imaging architecture methods. Improved ability to distinguish subtle differences in both hyper- and hypoechoic target regions in solid lesion-mimicking targets (a,b). Clear improvement in both spatial and contrast resolution in cystic-mimicking target regions (c,d) with more conspicuous anechoic appearance and more sharply defined internal borders noted especially in the far field.

a.

b.

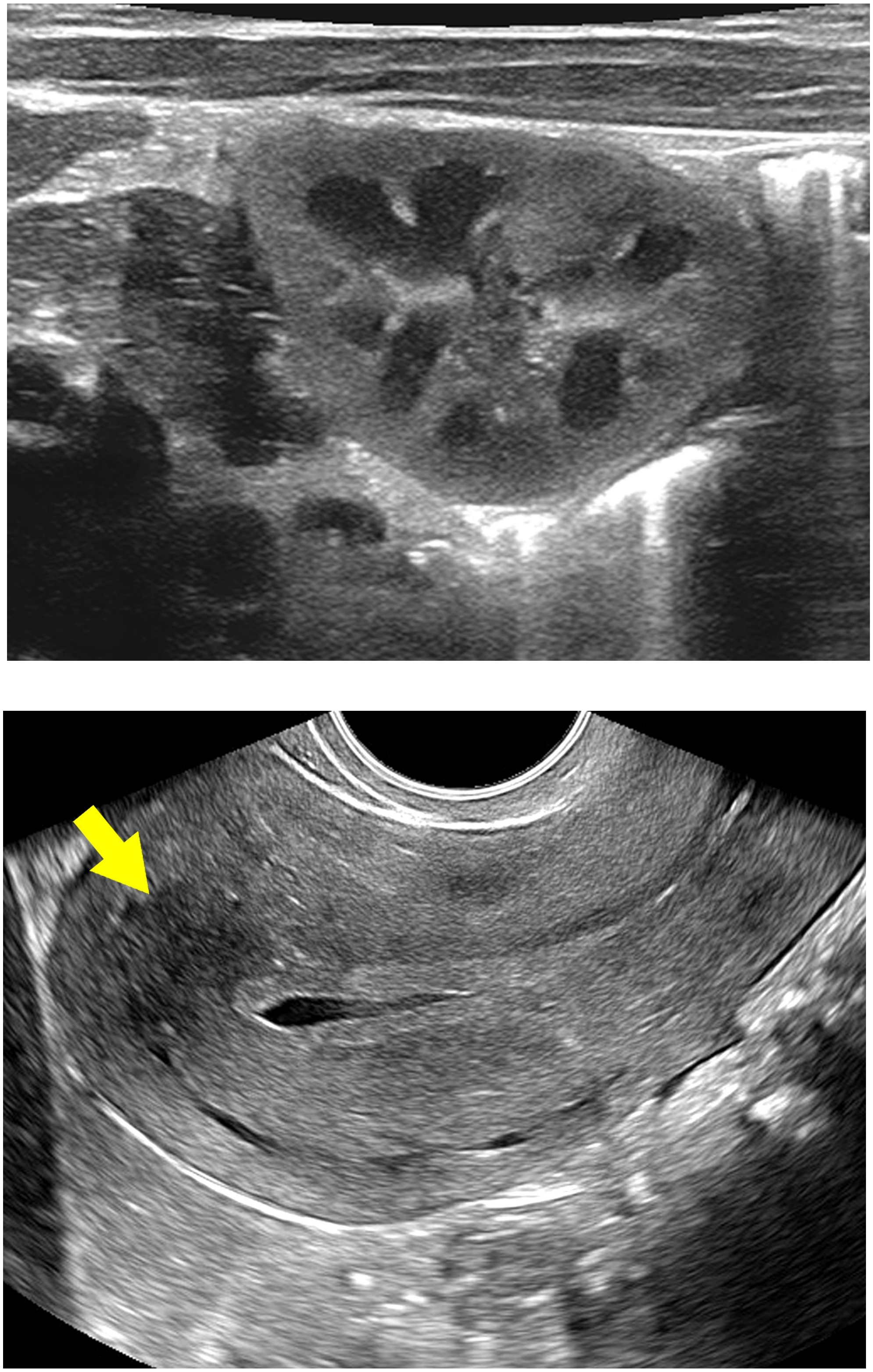

Figure 6: Big data with virtual beamforming — improved contrast resolution (clinical examples)

Clinical examples of improved *contrast resolution* made possible by virtual beam forming and the use of big data in creating two-dimensional gray-scale images. (a) Enhanced corticomedullary differentiation in a pediatric kidney. (b) Improved conspicuity of focal hypoechoic regions within the myometrium consistent with an intramural myoma (arrow).

Enhanced Digital Signal Processing (eDSP)

The enormous size and diversity of the acoustic data sets generated by virtual beamforming methods and captured by the power of big data would amount to nothing without technological capabilities to process this data and convert it into practical use. Enhanced digital signal processing (eDSP), the next pillar in advanced ultrasound imaging architecture, makes this possible. (Figure 2c) A digital signal is a discreet bit of electronic data, represented by a sequence of numbers, which is passed along a chain of hardware circuitry. In ultrasound imaging, these signals represent the acoustic information received by the transducer after an ultrasound beam interacts with human soft tissue.

Each individual point in the acquired data set is encoded with a number of acoustic characteristics that include: [9]

- Frequency (fundamental, harmonic)
- Phase
- Amplitude
- Attenuation metrics
- Particle displacement metrics
- Transmission velocity (sound speed)
- Scattering characteristics (linear vs. nonlinear backscatter, Rayleigh)
- Speckle characteristics and patterns

Digital signal processing is the method by which these and other parameters can be mathematically extracted from the raw data set for subsequent individualized processing and analysis. Software algorithms can identify, separate, group, and transform data points with similar characteristics and cluster them together into digital "siloes". This data segmenting provides the digital building blocks for all clinical ultrasound applications, i.e., 2D gray scale, 3D imaging, M-mode, Doppler, CEUS, elastography, as well as novel and emerging diagnostic capabilities. (Figure 7)

While digital signal processing methods have been around for decades, the integration of high speed, high capacity hardware components coupled with the development of cutting-edge industry-specific software and graphics capabilities elevates it to a new level, thus, *enhanced DSP* (eDSP). With the digital data stored in channel domain memory, multiple contemporaneous real-time and/or retrospective processing passes can be applied to each received data set at extremely fast rates. Channel domain memory, usually referred to simply as "computer memory", provides multiple locations for parking the data along the image creation chain where any number of state-of-the-art image processing functions can be applied simultaneously. The result is an exponential increase in the amount of data available for improved conventional ultrasound display modalities and for the development of new and emerging diagnostic capabilities.

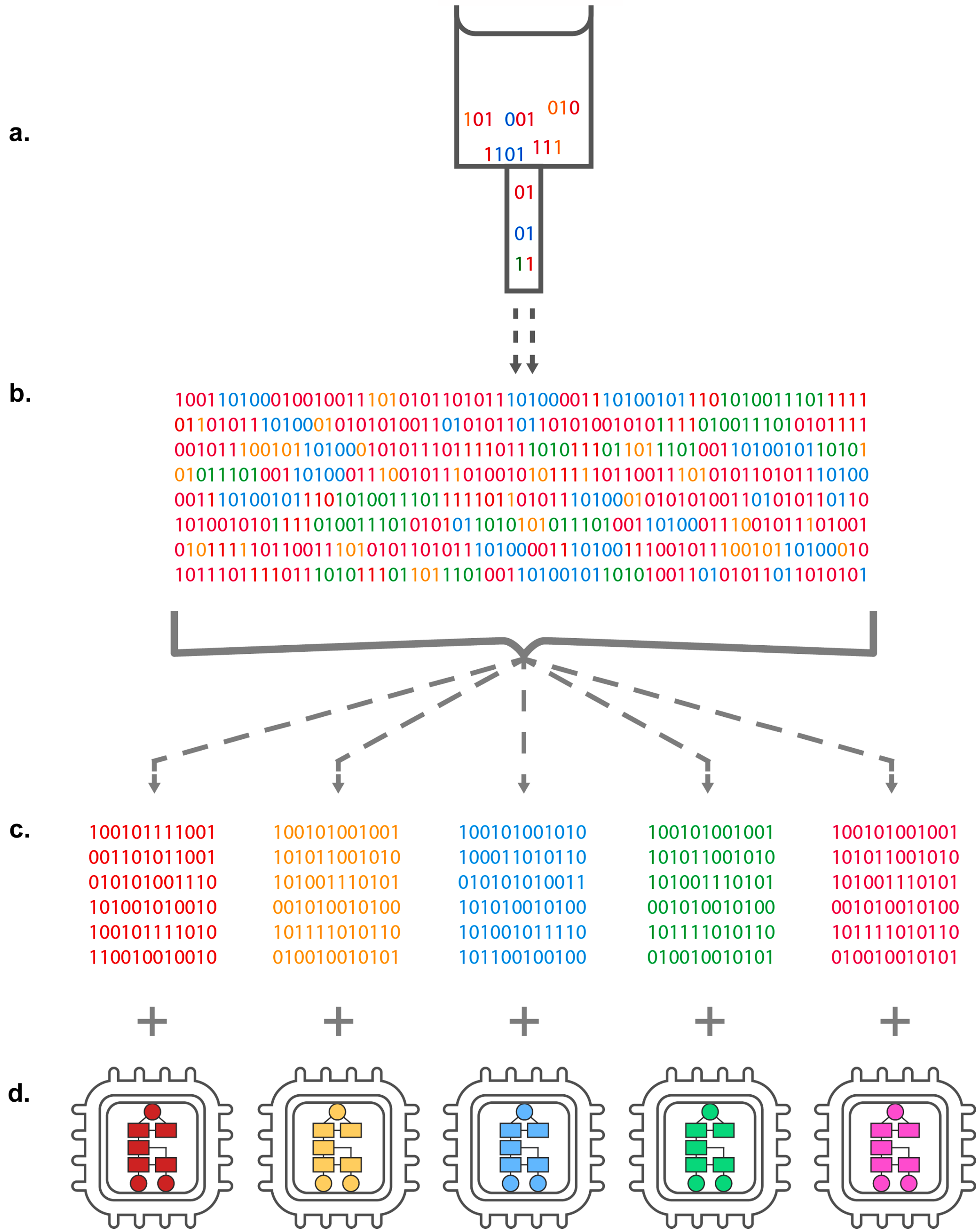

Figure 7: Digital data segmenting

Large complex acoustic data set received by the transducer (a) is sent directly to channel domain memory (b) where it is parsed, segmented, and siloed based on similar acoustic characteristics of individual data points (c). Unique, selected processing algorithms can be applied to each data set to achieve desired output results (d).

Benefits to clinical imaging associated with eDSP application to big data include:

- Improved temporal resolution: extremely fast back-end frame rates >1200 fps
- Introduction of novel diagnostic capabilities and modalities (Figure 8)
    - ◊ Automated sound speed compensation
    - ◊ Enhanced B-mode tissue characterization
    - ◊ Tissue transparency
    - ◊ Automated, RF generated B-mode measurements
    - ◊ Attenuation imaging

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a.

b.

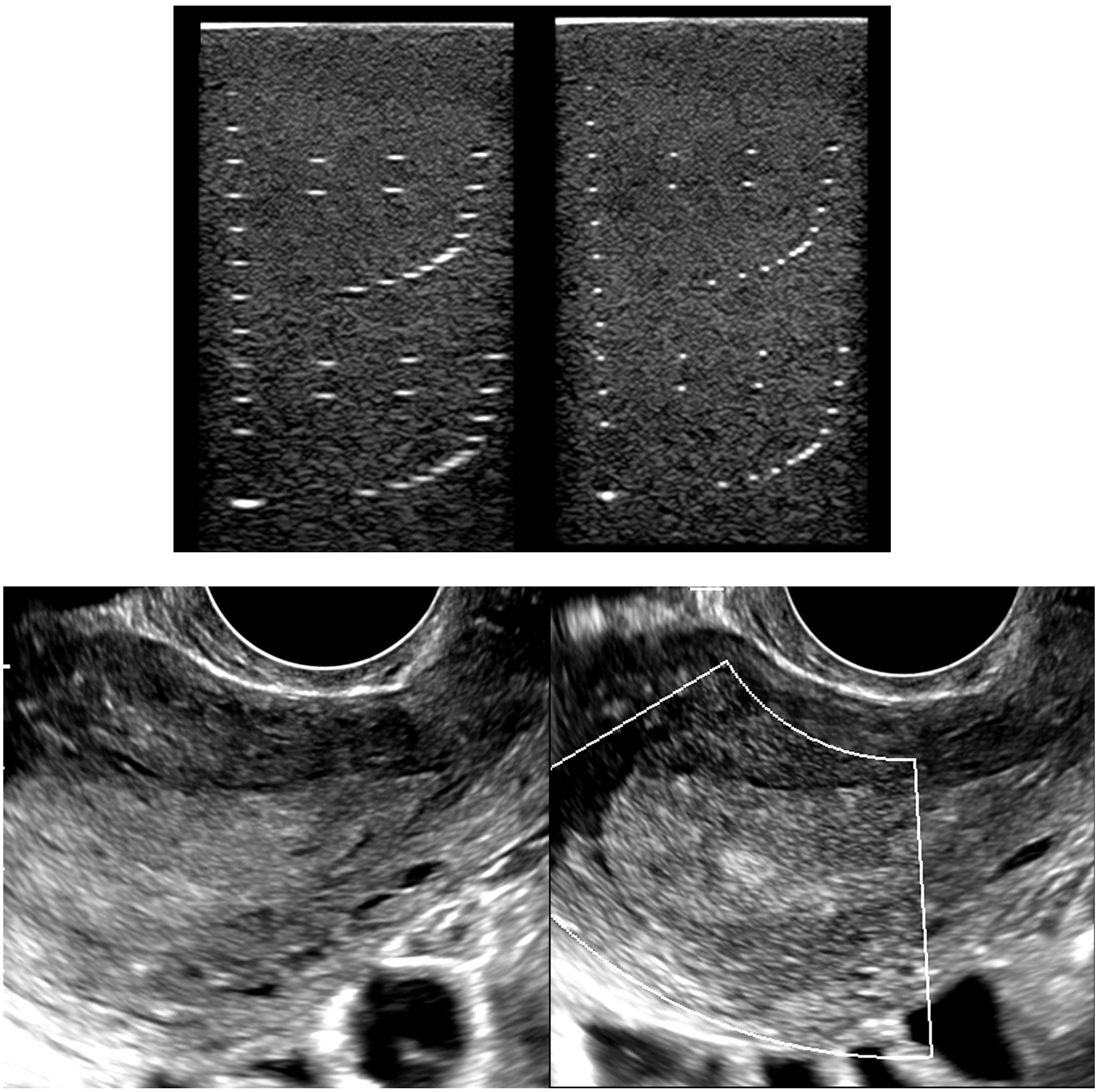


Figure 8: eDSP — novel diagnostic modalities

a. Enhanced spatial resolution from *automated sound speed compensation* which measures actual transmission velocity in different tissue types and recalibrates the imaging system accordingly.

b. *Enhanced B-mode tissue characterization* improves visualization of a uterine polyp based on difference in tissue signature between polyp and normal endometrial tissue.

c.

d.

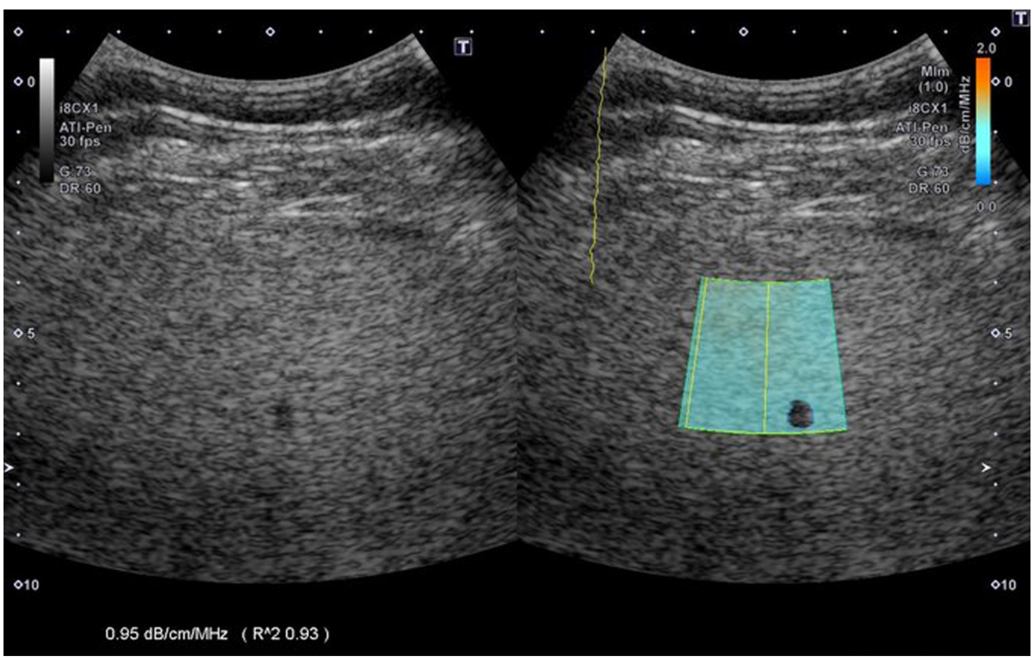


Figure 8 (cont.): eDSP — novel diagnostic modalities

c. Application of *tissue transparency* algorithms to fetal 3D imaging.

d. *Attenuation imaging*. Mapping of tissue-based differences in attenuation.

Bit-by-bit Frame Creation

For decades, ultrasound images were generated using a line-by-line frame creation schema. Data was received by the piezoelectric elements in a transducer array each of which was associated with a single transmit/receive channel. Each channel ultimately provided the output data that was stored in corresponding vertical lines in a scan converter which, finally, were displayed on a monitor as a series of single image frames. Data loss and limits on temporal resolution associated with this method placed constraints on image quality and diagnostic potential (Figure 1d). Bit-by-bit frame creation, on the other hand, uses big data sent directly from channel domain memory to fill a digital scaffold. These digital scaffolds are referred to as *back-end frames*, in contradistinction to *image* or, *front-end, frames*. Back-end frames are transparent to the operator; however, some are selected to create the conventional diagnostic modalities displayed on the image monitor. This explains the distinction between the extremely high frame rates possible on the back-end (≥1000 fps) and the more usual front-end, visual display frame rates (~16-60 fps). The ability to generate multiple back-end frames very quickly is one of the pillars that provides for consistent and uniform improvement in overall sonographic image quality. (Figure 2d) It is also integral to the development and deployment of advanced and emerging ultrasound diagnostic modalities.

Each big data point used to populate a back-end frame scaffold is typically plotted using Cartesian coordinates (x, y, z axes) although other mathematical approaches to data placement may be utilized. The specific acoustic parameters associated with each plotted data point are, essentially, selected by the operator. For example, if color Doppler mode is initiated on the console, data points representing Doppler blood flow parameters (i.e., frequency, phase, amplitude), will be plotted within the scaffold region associated with the on-screen color box to produce a color Doppler frame. Should the operator select real-time elastography mode, each frame will be filled with data bits representing particle displacement or shear wave velocity within the region of interest. Multi-modality display frames are generated from multiple data scaffolds each containing data bits representing one of the selected parameters and displayed simultaneously on the image monitor.

Bit-by-bit frame creation also results in significant improvement in spatial resolution and image uniformity as well as a reduction of image artifacts.[10] This is especially true with imaging in the far field. Virtual beamforming focuses each data point on both transmit and receive; big data and eDSP assure that each data point maintains the integrity of its encoded acoustic parameters. These pillars result in improved spatial and contrast quality throughout the imaging field. This is sometimes referred to as better "penetration"; however, true soft tissue penetration is a function of physical principles (transmit frequency and tissue attenuation characteristics). Another method of enhancing spatial resolution is *synthetic spatial compounding*.

Conventional spatial compounding requires the creation and integration of data acquired typically from three separate back-end frames each acquired at a different transmit/receive beam angle. The increased time required to build three frames reduces displayed frame rate and diminishes temporal resolution. Synthetic spatial compounding uses big data, eDSP methods, and bit-by-bit frame creation to amalgamate the data from three separate virtually created frames into a single frame which yields the improvement in spatial resolution. [11] (Figure 9)

Benefits to clinical imaging associated with bit-by-bit frame creation include:

- Improved temporal resolution with the ability to create back-end frame rates exceeding 1,000 frames/second (essential in newer applications and modalities)
- Reduced tissue motion artifact
- Reduction in imaging artifact display
- Creation of new temporal domain-based modalities: (Figure 10)
    - ◊ Vector flow imaging
    - ◊ Quantitative real-time CEUS
    - ◊ Quantitative real-time elastographic capabilities

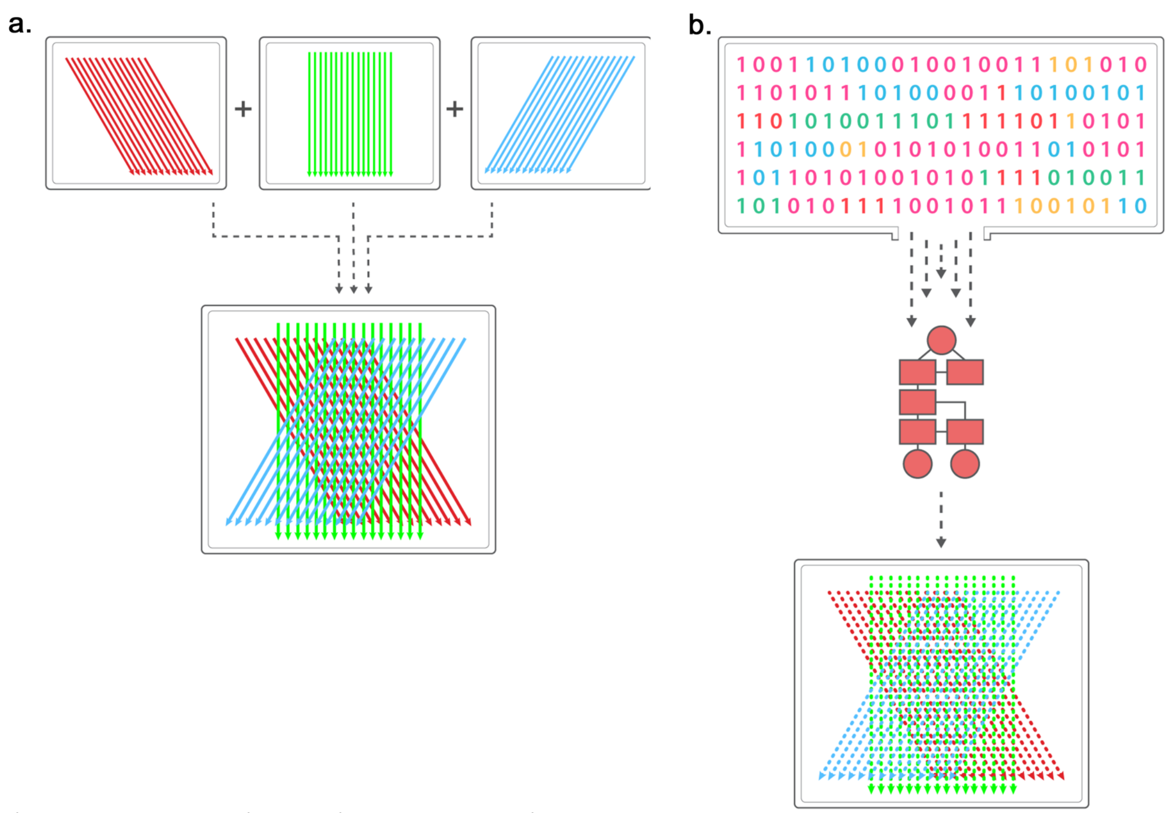
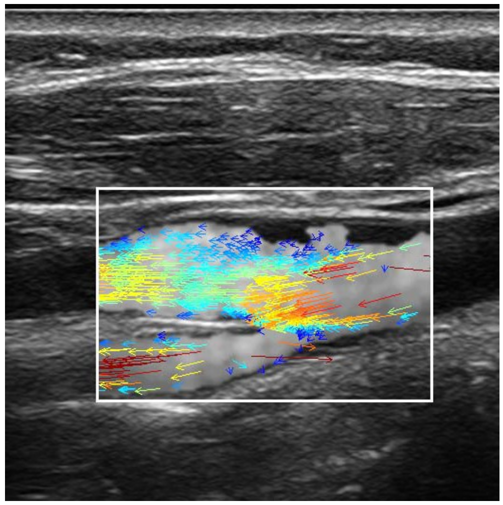


Figure 9: Synthetic spatial compounding

Conventional spatial compound requires the creation and integration of data acquired from typically three separate back-end frames (a). The increased time required to build three frames reduces displayed frame rate and diminishes temporal resolution. Synthetic spatial compounding uses eDSP methods to merge the data from several virtually created frames to achieve the desired improvement in spatial resolution (b).

a.



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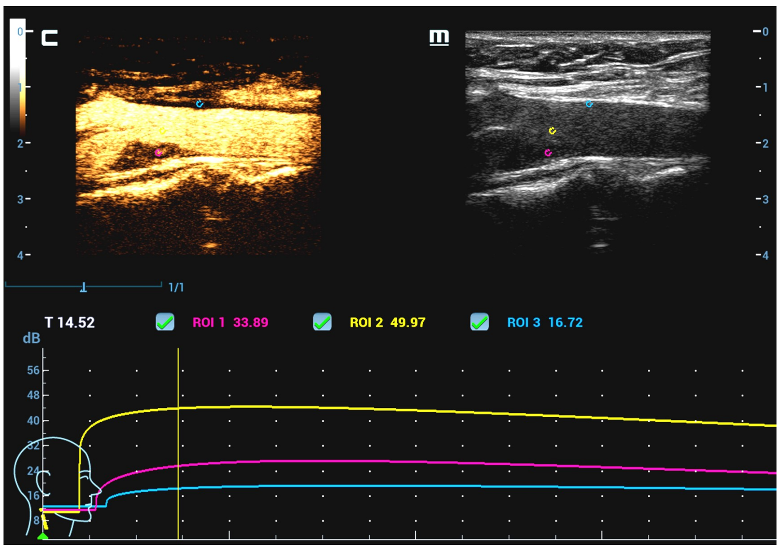

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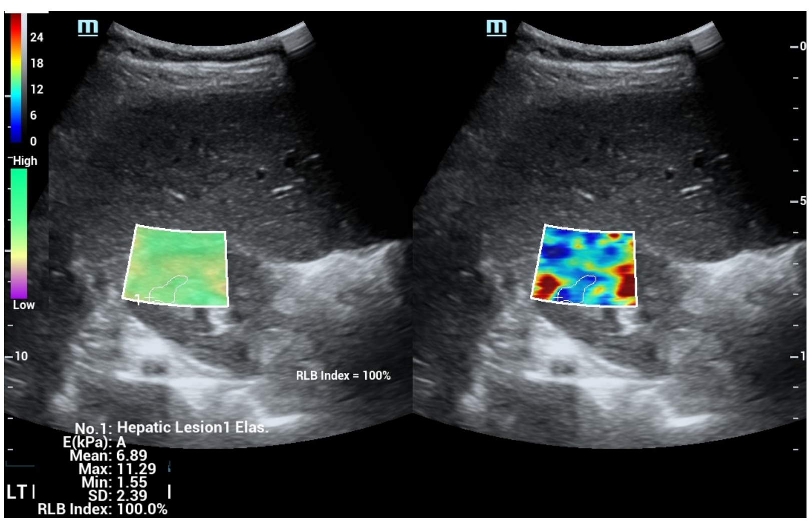

Figure 10: Bit-by-bit frame creation—novel diagnostic modalities

a. *Vector flow real-time imaging*. Non-Doppler speckle tracking display of hemodynamic states using color-coded quantitative arrows (vectors)

b. Quantitative contrast-enhanced ultrasound

c. Quantitative real-time elastography

Conclusion

Advanced ultrasound imaging architecture results in consistently and reliably improved sonographic diagnostic capabilities. Generated by virtual beamforming methods, the enormous acquired acoustic data set is captured and transferred by high-capacity, high-speed big data methods into channel domain memory for enhanced digital signal processing. The processed data output is then assembled bit-by-bit into back-end digital data frames that provide the underpinning for all enhanced conventional and emerging sonographic modalities. While the four pillars described in this article are presented as conceptually discrete, they are concretely and integrally intertwined in elevating sonographic diagnostic capabilities to the next level.

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