AIXPLORER MultiWave

White Paper

SuperSonic imagine
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UltraFast™ Doppler

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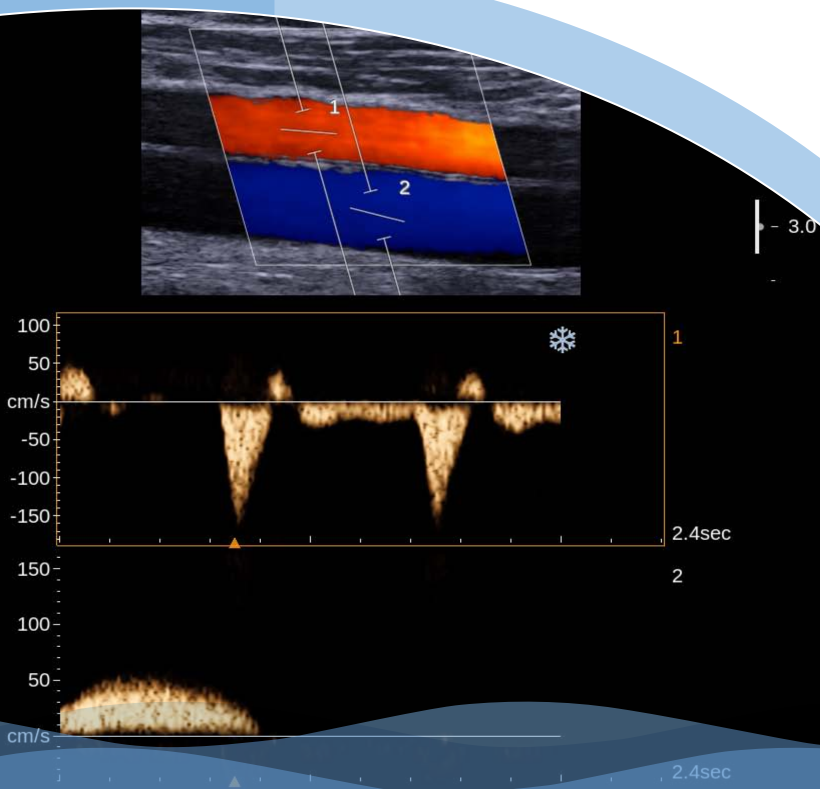

1. Introduction

Doppler-based techniques are well established tools on ultrasound imaging systems for flow analysis and quantification, and have become indispensable in the context of cardiovascular disease and cancer assessment. There are currently two different kinds of Doppler techniques available: Spectral Doppler analysis (continuous-wave or CW, and pulsed-wave or PW), and color Doppler flow velocity and/or power imaging *(Jensen, 1996; Evans and McDicken, 2000; Szabo, 2004)*.

PW Doppler provides detailed quantification of flow characteristics by acquiring Doppler signals within a limited spatial region at very high sampling rates. Flow quantification is then typically available only at a single location (sample volume), or multiple locations along the same line (axial multi-gating). Color Doppler overcomes the limited spatial sampling of PW Doppler by sacrificing the detailed quantitative analysis in order to transmit ultrasound firings and acquire Doppler signals over a relatively large 2D region of interest. The information displayed is the mean flow velocity and/or Doppler power estimated from a small number of firings. Color Doppler images are displayed in real time at frame rates that are usually around a few Hz. In their daily workflow, physicians need constantly to deal with this trade-off between flow imaging with a large field of view and detailed flow quantification at one location.

UltraFast™ imaging represents an opportunity to overcome those limitations and create a new paradigm in ultrasound-based flow analysis by merging color Doppler and PW Doppler in one feature: UltraFast™ Doppler.

UltraFast ultrasound imaging was introduced to the market in 2009 on the Aixplorer® ultrasound system, which can acquire image information at frame rates of up to several thousands of Hz, an increase by a factor of 100 relative to conventional ultrasound systems. This unique capability enabled the visualization of radiation-force induced shear waves and the measurement of the shear wave propagation speed, which led to a new imaging technology called "ShearWave™ Elastography" or SWE™. SWE provides real-time quantification* of tissue elasticity *(Bercoff et al, 2004)*.

Today, UltraFast imaging is being applied in new ways. As will be described in this paper, UltraFast imaging can be used to both visualize and quantify flow, hence combining the utility of color flow and PW in a single feature. In the context of flow analysis UltraFast Doppler provides high frame rates, high sensitivity and fully-quantifiable flow information over a large region of interest. The reinvention of Doppler ultrasound through UltraFast imaging has a potential major impact on physician's workflow, examination time and diagnostic accuracy.

* *Quantification tool available outside the USA*

2. UltraFast™ Ultrasound Imaging

2.1 Conventional Ultrasound Imaging

Ultrasound imaging is usually performed by sequential insonifications of the medium using focused beams. Each focused beam enables the reconstruction of one image line. A typical 2D image is made of a few hundred lines (64 to 512). The overall sequence is illustrated in Figure 1. The frame rate of the imaging mode is determined by the time required to transmit a beam, receive and process the backscattered echoes from the medium and repeat that for all the lines of the image.

In conventional ultrasound imaging, the time to build an image is:

$$T_{image} = \frac{N_{lines} * 2 * Z}{c} \qquad (1)$$

where Z is the image depth, c the speed of sound assumed constant (1540 m/s) and N is the number of lines in the image.

The maximum frame rate that can be reached with this technique is:

$$FR_{\max} = \frac{1}{T_{image}} \qquad (2)$$

For example, an image of 5 cm in depth and 256 lines in width corresponds to a maximum frame rate of 60 Hz.

Originally, ultrasound system architectures were designed to support this scheme by processing one image line at a time. Despite being acceptable for most common applications, this induced significant constraints in high-frame rate applications such as echocardiography or 4D imaging.

Parallel beamforming (multiline) schemes have been considered to overcome these limitations. In the academic literature, such schemes have been reported as early as the end of the 70's *(Delannoy et al, 1979; Shattuck et al, 1984; Von Ramm et al, 1991)*. Most current systems have multiline capabilities: for each transmit beam, several receive lines (typically from 2 to 16) are computed. Multiline processing can be used either to increase the frame rate (for example, in echocardiography) or to increase the number of lines computed per image (for example, in 3D imaging).

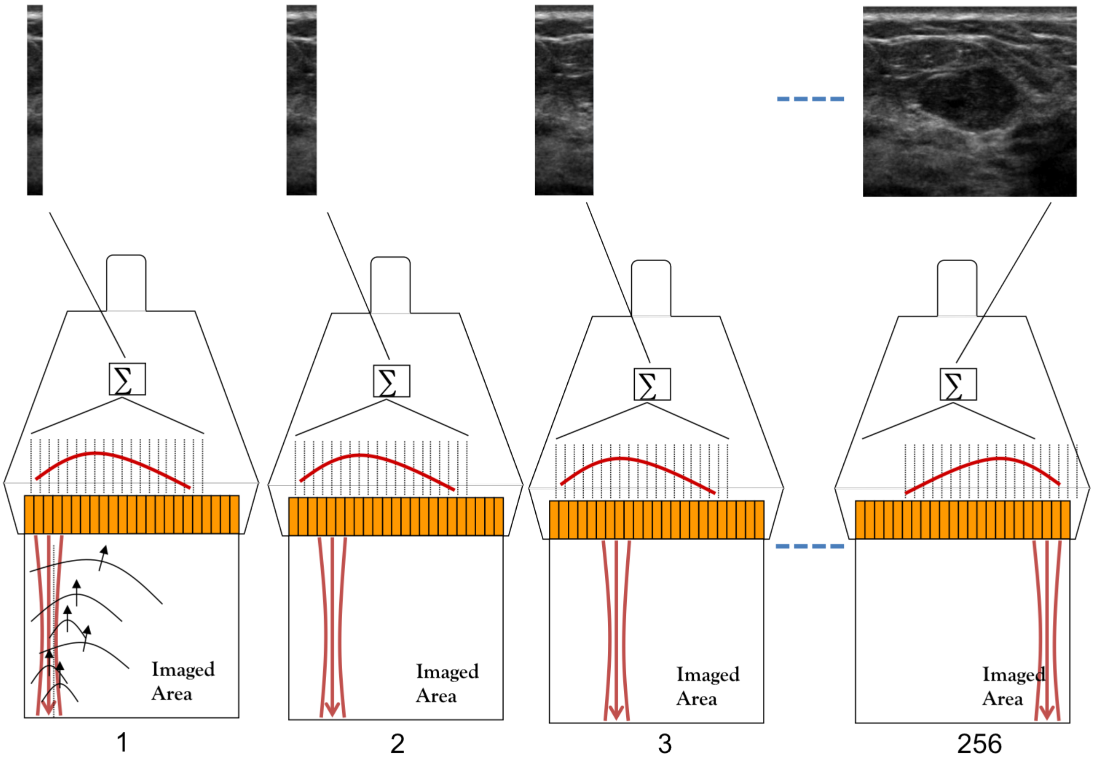

Figure 1 : Conventional imaging acquisition process.

2.2 UltraFast Imaging

With or without multiline capabilities, current ultrasound systems are built on a serialized architecture and images are reconstructed sequentially from several equivalent transmits.

UltraFast imaging represents a radical departure from this approach. An ultrafast imaging system is able to compute in parallel as many lines as requested and is therefore capable of computing a full image from a single transmit, irrespective of the image size and other characteristics. In such a system, the image frame rate is no longer limited by the number of lines reconstructed but by the time of flight of a single pulse to propagate through the medium and return to the transducer. There are many ways to leverage an ultrafast imaging architecture *(Lu, 1998; Jensen 2005)*. SuperSonic Imagine's approach is based on the use of plane wave insonification *(Montaldo et al, 2009)*. A plane wave is generated by applying flat delays on the transmit elements of the ultrasound probe as illustrated on Figure 2. The generated wave insonifies at once the whole area of interest.

The backscattered echoes are then recorded and processed by the ultrafast scanner to compute an image of the insonified area.

Plane wave imaging allows the computation of one full ultrasound image per transmit.

UltraFast imaging allows significant increase of the maximum frame rate achievable by an ultrasound system.

Table 1 lists typical frame rates for different ultrasound clinical applications using conventional and ultrafast architectures.

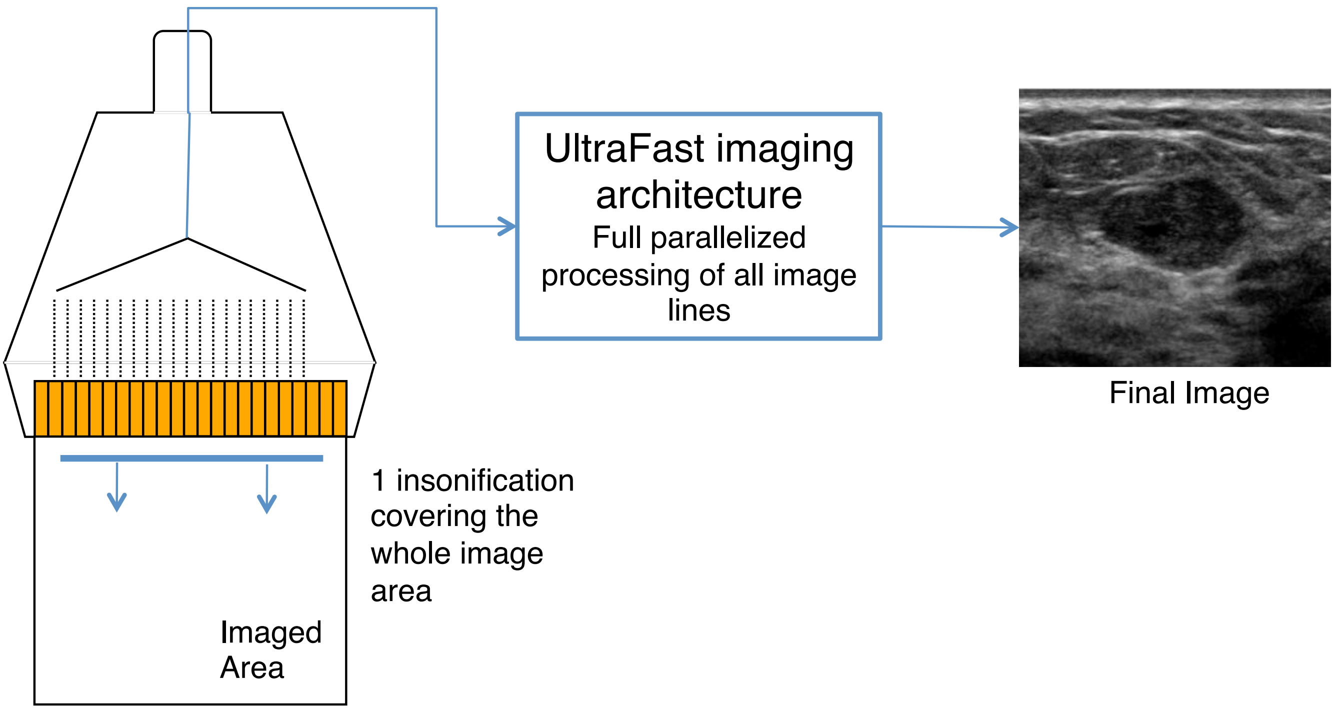

Figure 2 : A plane wave is transmitted by a linear transducer and insonifies the whole region of interest. An ultrasound image is computed from this single insonification.

Application	Typical imaging depth	Conventional architecture	UltraFast architecture
Abdominal imaging	20 cm	20 Hz	3,800 Hz
Cardiac imaging	15 cm	150 Hz	5,000 Hz
Breast imaging	5 cm	60 Hz	15,000 Hz

Table 1. Examples of typical frame rates in different clinical applications for conventional and ultrafast architectures.

In UltraFast imaging, the beamforming computations must be performed on a fully parallelized architecture, typically based on a software platform.

Two technological barriers need to be overcome to build a fully software-based platform:

- The data transfer rate from the acquisition module to the processing unit. As raw (non beamformed) Radio Frequency (RF) signals are directly transferred to the PC, the data rate required to perform real time imaging is immense (several GigaBytes/s).
- The processing unit needs to be powerful enough to ensure real time beamforming. As an example, conventional gray scale imaging requires 1 to 2 Gigaflops (multiplication+addition) per second.

Figure 3 represents the architecture of an ultrafast system compared to a conventional one.

Aixplorer is the first commercially available system to break these technological barriers and allows ultrafast imaging of tissue with frame rates up to 20,000 Hz. It relies on the use of powerful graphical processing units (GPUs) from the video game industry combined with fast digital links (PCI express technology) capable of transferring massive volumes of data to these units.

The next section demonstrates how UltraFast imaging can be used to improve Doppler flow analysis by addressing important performance and workflow constraints of the currently available color and PW Doppler modes.

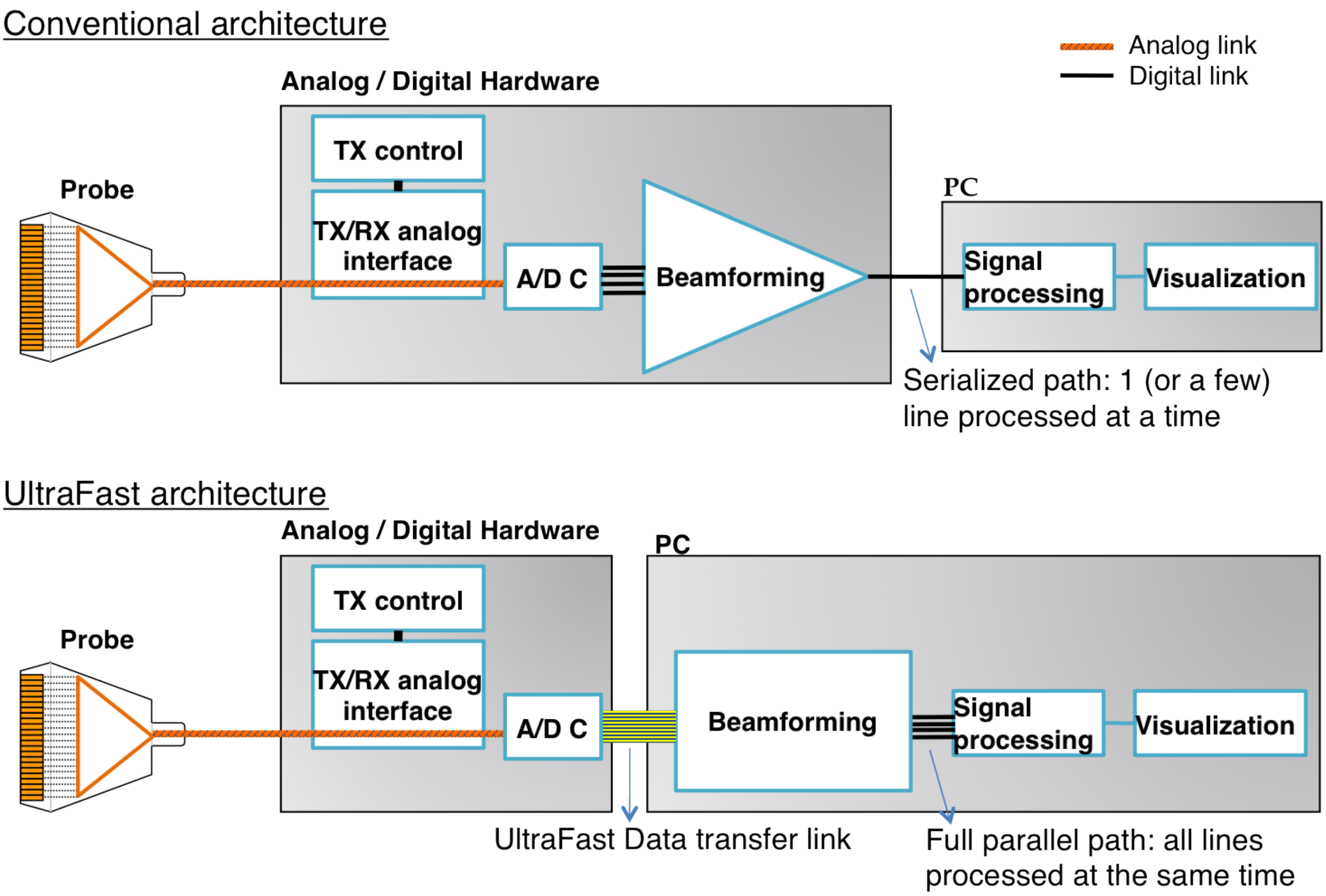

Figure 3 : Conventional (top) vs. UltraFast architecture (bottom). As beamforming is performed in software in the UltraFast architecture, full parallelization of image formation can be performed. Each insonification can therefore lead to a full image.

3. UltraFast™ Doppler: UltraFast™ Imaging for Flow Quantification.

Doppler analysis is one of the most demanding features of an ultrasound system, both from a technical standpoint, since the number and complexity of firings to acquire the information is very high, and from a performance standpoint as quantitative measurements are expected. These constraints raise the requirements of the mode in terms of accuracy and reproducibility. Due to this complexity, Doppler modes suffer from technical limitations that impact the user in a significant way. UltraFast imaging can overcome those limitations and will open new perspectives in Doppler analysis both in terms of performance and user workflow.

3.1 Conventional Doppler Imaging

Color Doppler imaging:

In color Doppler imaging, flow velocity estimation relies on the use of N narrowband pulses transmitted at a constant pulse repetition frequency (PRF) to estimate the Doppler frequency and/or power. N is commonly referred to as the color ensemble length and usually varies between 6 and 16 pulses. In a typical case, each ultrasound line is insonified N times. Acquisition and processing are done sequentially line by line as illustrated in Figure 4. The main processing steps are wall filtering to extract Doppler blood flow signals from the much stronger tissue echoes, and estimation of the mean flow velocity, mostly using correlation-based methods *(Kasai et al, 1985; Bonnefous and Pesque, 1986; Loupas et al, 1995)*.

PW Spectral Doppler:

To achieve full quantification of Doppler signals by means of spectral analysis, the ensemble length N must be multiplied by approximately an order of magnitude, corresponding to 50 to 100 temporal Doppler samples per pixel. FFT-based spectral analysis is utilized to deduce the full distribution of Doppler velocities within the sample volume. The results of the spectral analysis are then displayed as a velocity vs. time sonogram, as illustrated in Figure 4. Since the long ensemble length does not allow real time scanning along different lines, information is usually only gathered at a single location or a few locations along a given ultrasound beam (axial multigating).

Conventional Doppler analysis is therefore performed using two distinct ultrasound modes:

- Color Doppler imaging to spatially locate a flow region of interest.
- PW spectral Doppler to perform quantitative measurements in the flow region of interest depicted by color Doppler imaging.

In a typical Doppler exam, the user constantly goes back and forth between those two modes and successively analyzes with PW Spectral Doppler the locations pointed out by the color flow imaging mode.

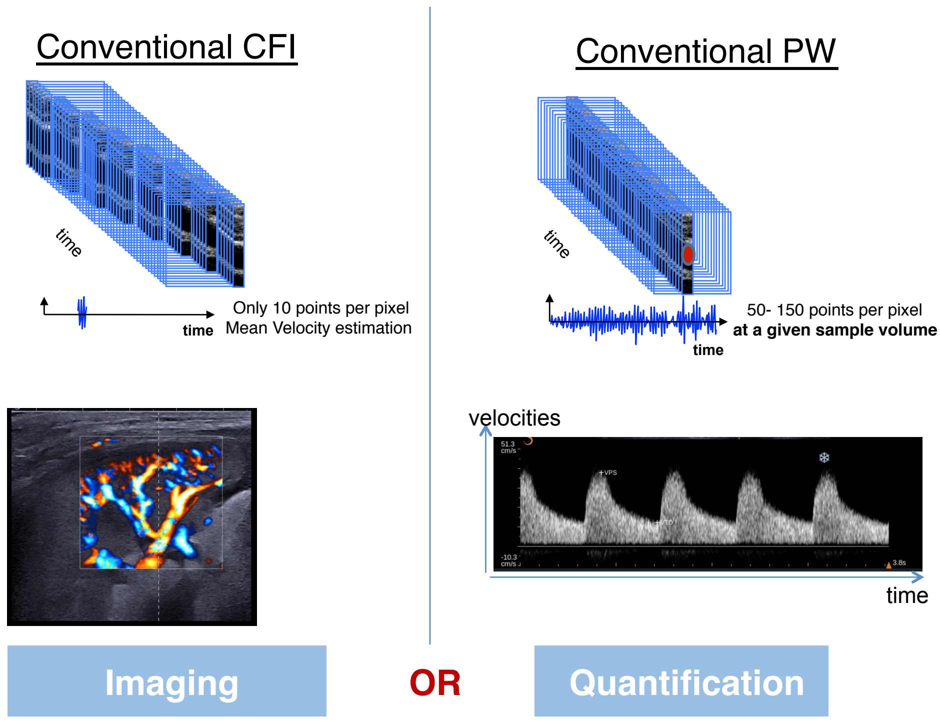

Figure 4 : Conventional ultrasound flow visualization and analysis modes.

3.2 UltraFast Doppler Imaging

In UltraFast Doppler, several tilted plane waves are transmitted into the medium and the backscattered echoes are coherently summed to reconstruct ultrasound images *(Bercoff et al, 2011)*. (Figure 5)

The maximum number of angles that can be used to compute an image is limited by the acquisition Pulse Repetition Frequency ($PRF_{Doppler}$) needed to measure the desired Doppler velocity scale (usually the velocity scale is set by the user).

$$Nangles = \frac{PRF_{max}}{PRF_{Doppler}} \quad (3)$$

where PRF_{max} is the maximum PRF that can be achieved for a given imaging depth.

Using UltraFast imaging, Doppler information is continuously and simultaneously acquired across the full image. Therefore, unlike conventional color Doppler acquisitions, all pixels are sampled at a high Doppler PRF in an uninterrupted and concurrent manner, offering the unique ability to perform full flow quantification at every pixel within the UltraFast color box.

In a typical implementation of UltraFast Doppler, a single-shot acquisition can be launched from the conventional color Doppler imaging mode. A full clip of UltraFast Doppler data is acquired (typically 2 to 4 s) and the system is frozen. The user can then review the UltraFast color flow imaging clip, select the frame(s) offering best visualization of the flow properties of interest, and perform full spectral analysis at every pixel of the color box in a retrospective manner.

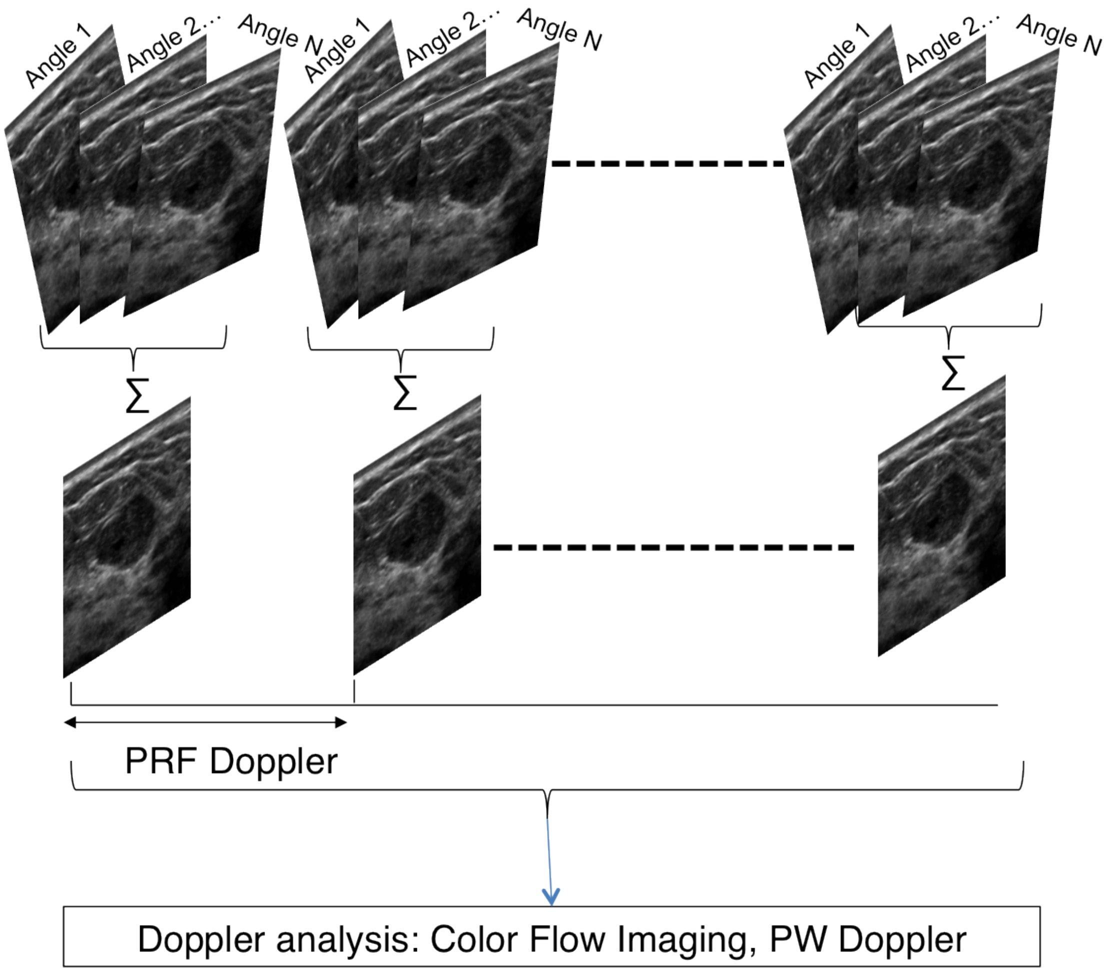

Figure 5 : UltraFast compound imaging for Doppler analysis of flow.

Figure 6 describes the acquisition workflow in UltraFast Doppler.

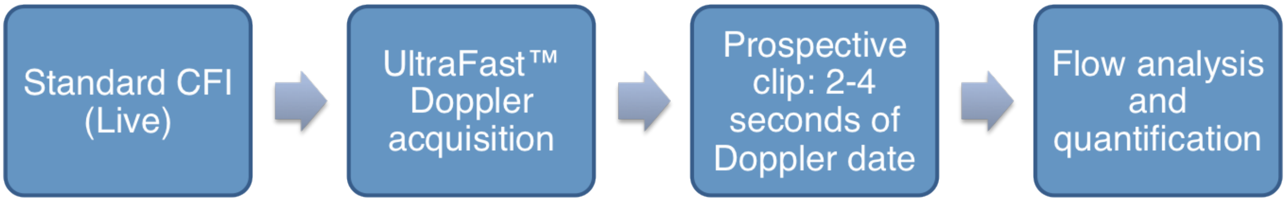

Figure 6 : UltraFast acquisition workflow

Retrospective UltraFast spectral analysis offers for the first time the ability to compare flow spectra and measurements from multiple locations, which have been acquired simultaneously and therefore correspond to the same cardiac cycle and exhibit perfect temporal synchronicity.

UltraFast Doppler offers:

- A significant improvement of color flow imaging performance in terms of temporal resolution and sensitivity.
- A new Doppler paradigm by merging the color Doppler and PW Doppler modes in a single fully-quantifiable acquisition, which can simplify workflow, reduce exam time, and can enable advanced measurement and visualization capabilities.

3.3 Improving Color Doppler Imaging

Conventional color Doppler imaging offers limited frame rates (typically 20 Hz) and suffers from severe trade-offs between color box size and temporal resolution. Figure 7 shows two conventional color Doppler frames from a femoral artery, plus the corresponding frames obtained by means of UltraFast Doppler.

In this example, UltraFast Doppler exhibits excellent flow sensitivity, and provides frame rates of more than 80 Hz. On the other hand, conventional color Doppler imaging is limited to a frame rate of 19 Hz which results in insufficient sampling of the underlying flow dynamics, as illustrated by the bottom frames of Figure 7 where the reverse flow is perfectly documented in the UltraFast Doppler frame, but is completely missed by the conventional color Doppler acquisition. This example demonstrates how limited frame rates can induce a loss of information, something that can represent a major issue in the context of flow pathology.

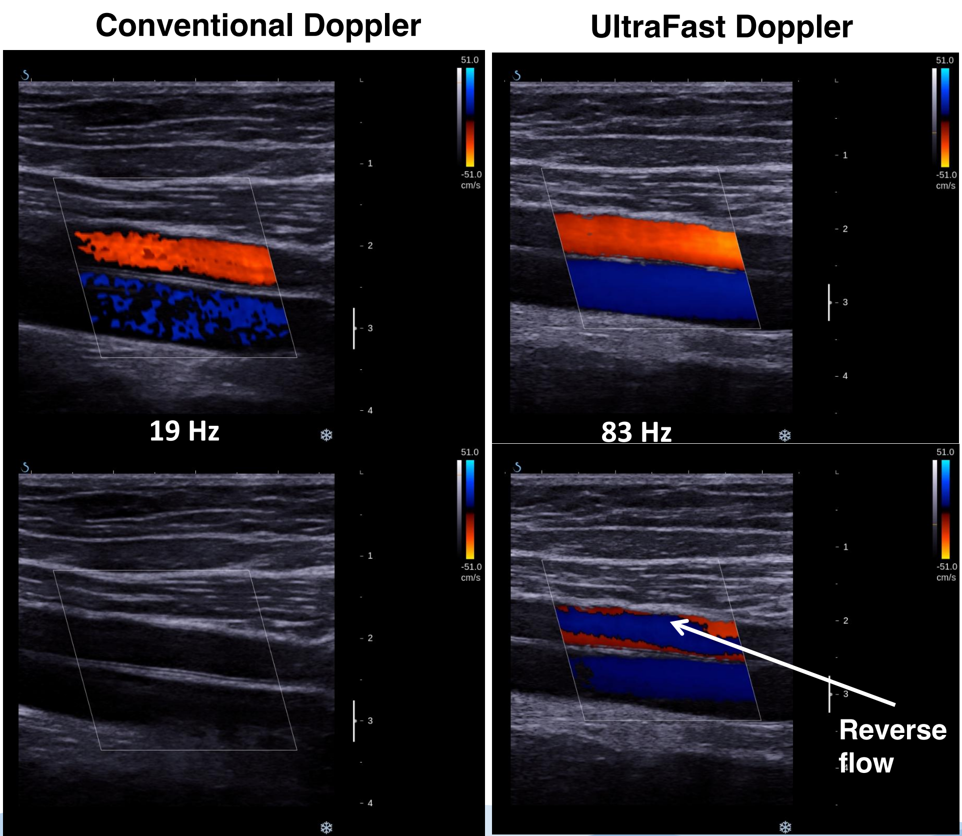

Figure 7 : UltraFast color flow imaging provides increased temporal resolution and better sensitivity allowing much finer analysis of flow.

UltraFast Doppler enables frame rate increases by a factor of 5 to 10 compared to conventional color Doppler, typically from 60 up to 200Hz, without sacrificing field of view or spatial resolution. Thanks to these improvements, complex flow dynamics and transient flow event can be visualized in a much more accurate manner, potentially leading to a more reliable hemodynamic assessment of cardiovascular diseases such as stenosis.

Compared to conventional color Doppler imaging, UltraFast Doppler acquisitions bring several advantages to the end user:

- Clips of color data can be generated with high sensitivity, and frame rates up to a factor 10 relative to conventional systems.
- The increased quality is maintained regardless of the color box size. Conventional color Doppler suffers from trade-offs between frame rate and color box size. Using plane waves, the whole area of interest can be filled with color Doppler information without any drop in frame rate.
- The flow information is consistent and synchronous throughout the imaged area, since the Doppler signals corresponding to all pixels are acquired at the same time. In contrast, conventional color Doppler lines are sequentially acquired, so that the Doppler signals on the sides of the color box exhibit time lags that can reach several hundreds of milliseconds.

3.4 Flow Quantification Anywhere

In addition to increased flow imaging performance, UltraFast Doppler enables full quantification of flow data everywhere in the image. The user can position a sample volume anywhere within the region of interest and the system responds by instantaneously computing and displaying the PW spectrogram from the selected location. Up to three spectrograms can be calculated and displayed simultaneously on the image as illustrated in Figure 8.

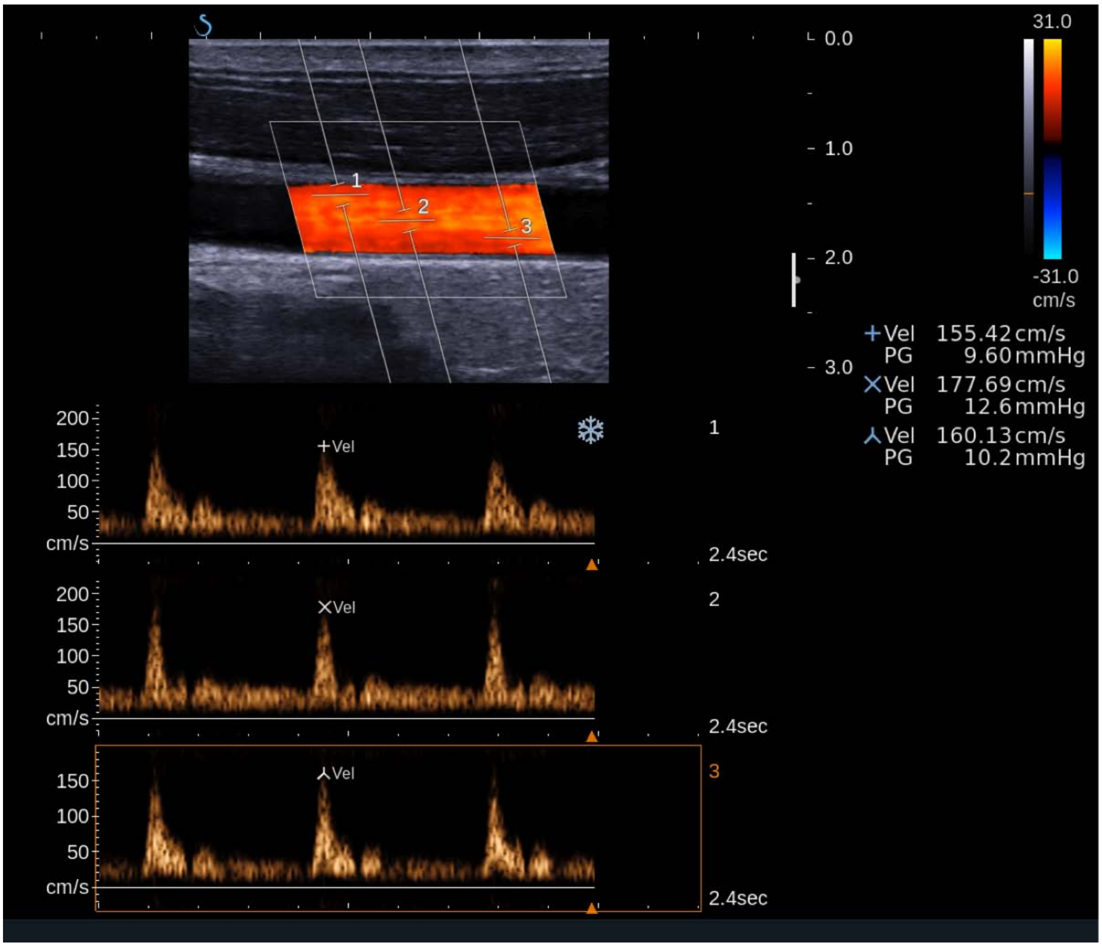

Figure 8 : Simultaneous UltraFast Doppler spectral analysis from three sample volumes

Measurements can be performed independently on all spectrograms and compared to each other with a high degree of reliability, since all spectra are computed from data acquired at the same time, on the same cardiac cycles.

It is important to note that the results of UltraFast spectral analysis are numerically equivalent to those obtained by a conventional PW Doppler exam performed under the same conditions. Figure 9 shows a comparison between peak systolic velocities (PSV) and end diastolic velocity (EDV) measurements in a flow phantom mimicking arterial flow for both techniques (Conventional PW and UltraFast Doppler). This comparison demonstrates that the PSV and EDV measurements show excellent correlation over a wide range of velocities.

As a final example, Figure 10 displays UltraFast Doppler results from a femoral artery and vein (same case as Fig 7), depicting the arterial and venous flow corresponding to a given color frame (top), and documenting the full temporal evolution of flow within each vessel in the two UltraFast spectrograms (bottom) .

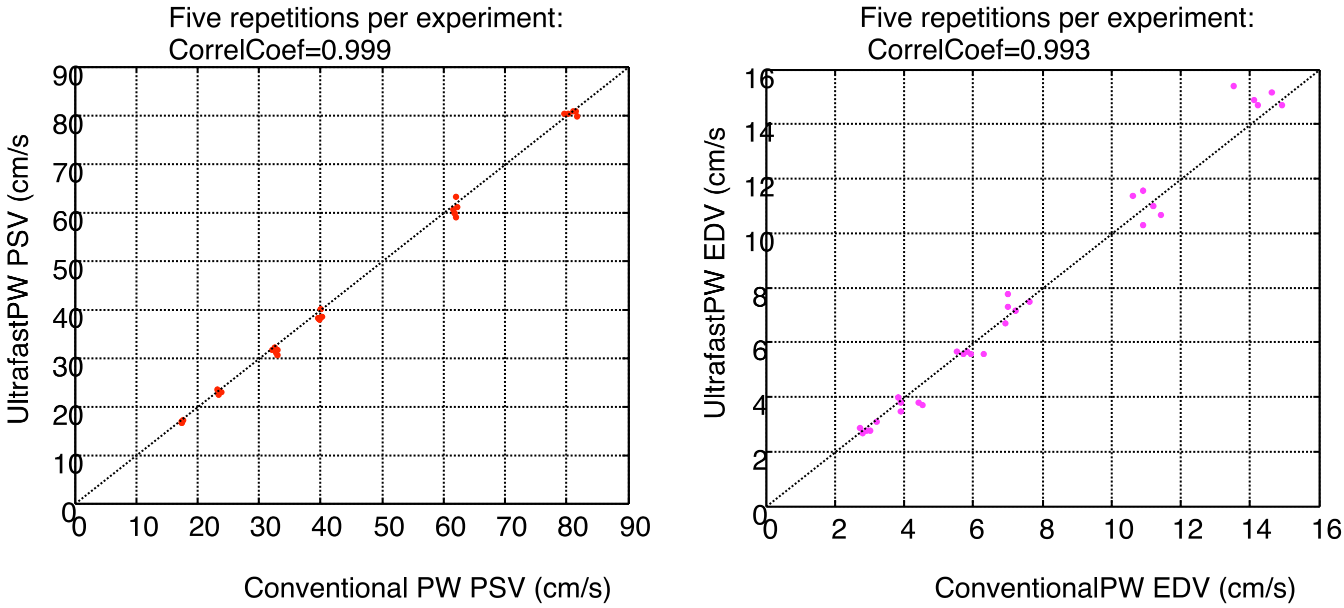

Figure 9 : Conventional vs UltraFast PW measurements for different velocities. PSV (left) and EDV (right).

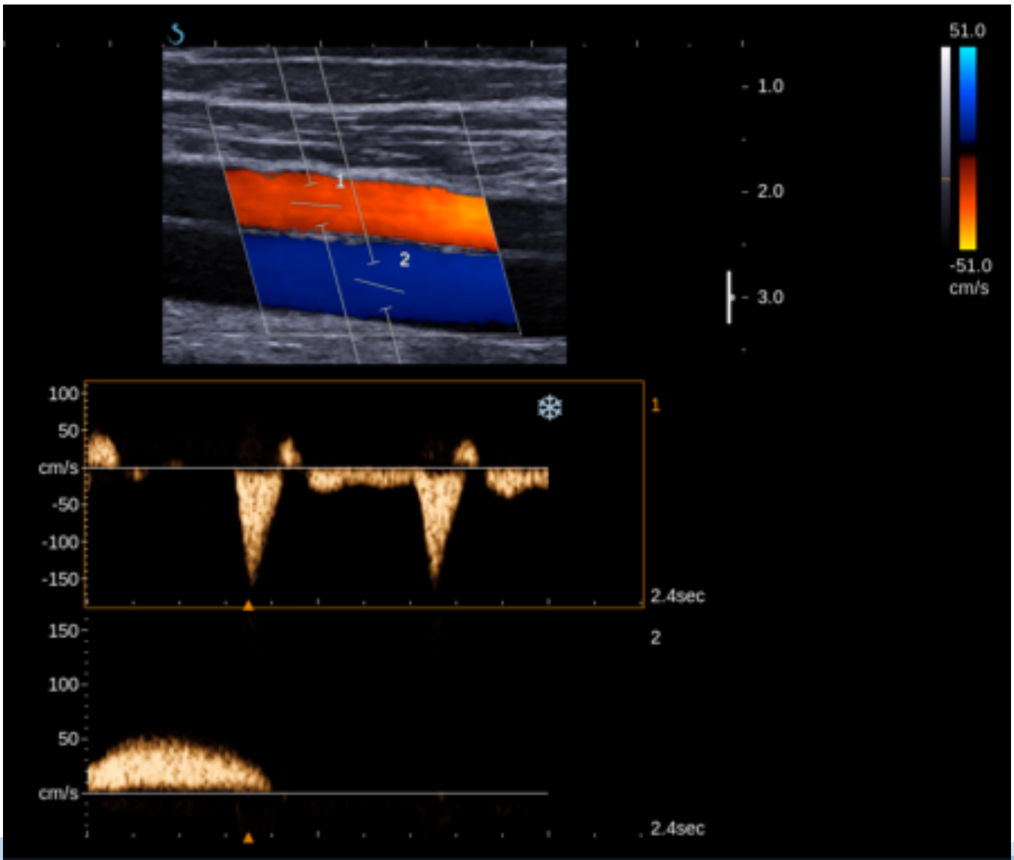

Figure 10 : UltraFast spectrograms derived from the femoral artery and vein

4. Conclusion

UltraFast imaging is a breakthrough technology that can offer significant performance improvements and innovative capabilities to the field of medical ultrasound. UltraFast Doppler is the combination of UltraFast imaging and Doppler techniques, which retain the advantages of color Doppler and PW Doppler without the respective disadvantages of each individual mode. UltraFast Doppler offers high-sensitivity and high-frame rate flow imaging allowing high-quality visualization of complex and transient flow events, plus the ability to perform accurate quantification and comparison of flow velocities through the whole image area based on full spectral analysis. Due to these characteristics, UltraFast Doppler has the potential to significantly simplify the workflow of Doppler exams and reduce the time needed to complete them. New UltraFast Doppler features and capabilities are currently under development, which will undoubtedly enhance the clinical utility of Doppler imaging even further.

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