cSound 2.0

Vivid E95

Background

Through the Healthymagination initiative, GE Healthcare continuously invests in innovations that help lower the cost, increase access, and improve the quality of healthcare. Since the introduction of the Vivid™ technology platform in 2000, GE's cardiovascular imaging team has pioneered developments in image processing, beamforming and image display. As an example, the Vivid *i* was the GE's first high-performance miniaturized cardiovascular ultrasound system, that GE's engineers developed by miniaturizing the components of a premium echocardiography system weighing more than 400 pounds (180 kilograms), to provide a portable system weighing only 11 pounds (less than five kilograms). In 2015, the Vivid S60, Vivid S70, Vivid E90 and Vivid E95 were launched. These products were based on the cSound™ platform — taking image quality to a new level. cSound is the engine that provides unprecedented image quality. This is made possible by intelligent image reconstruction in software. cSound provides flexibility for future enhancements. The feedback on these products has been tremendous – but as you will discover in this paper, this was only the beginning. This paper will focus primarily on the Vivid E95. As a cardiovascular ultrasound industry first, the Vivid E95 has an easily upgradable beamformer implementation. In this paper, we will explore in detail what this means to our customers. This paper describes features that are made possible with cSound's next generation algorithms both for existing features (Enhancements) and newly introduced features in July 2017 (New). To give you a sense of how the cSound platform may evolve in the future, we have also included two sections describing features that are still in development marked as **In development**.

These sections represent ongoing product research and development efforts. These research and development efforts ***are not products and may never become products.***

cSound Architecture

Every patient is different as anyone working in medical ultrasound can attest. Even the best ultrasound system may fall short when used on a very difficult to scan patient. The cSound architecture was designed from the ground up to overcome some of the fundamental limitations of today's ultrasound systems, aiming to make imaging less patient body habitus dependent.

GE's cSound platform introduces a new level of versatility, flexibility and processing power in image acquisition, reconstruction and visualization. The main component in the new platform is a fully configurable software image processing chain. The figures below illustrate the TruScan and Accelerated Volume Architecture (Figure 2) used in our prior generation scanners, as well as the cSound architecture (Figure 3) used in our Vivid S60/70 and Vivid E90/95 scanners.

Figure 1: Vivid S60/S70 and E90/95; first GE systems built upon the cSound platform

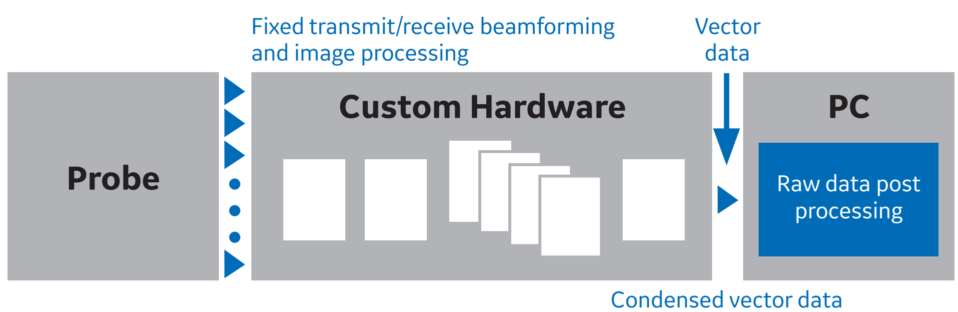

Figure 2: TruScan and Accelerated Volume Architecture

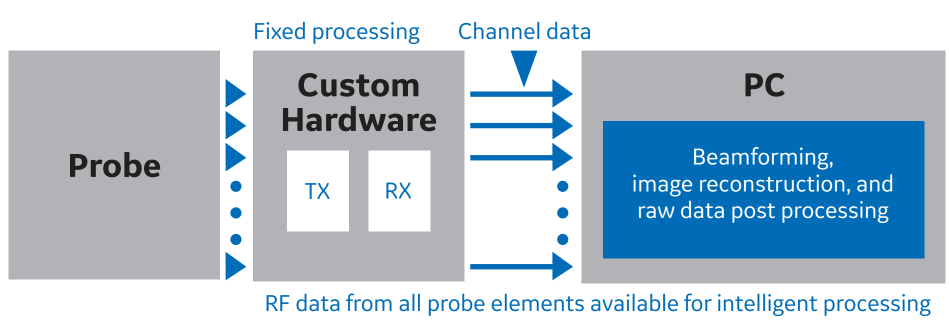

Figure 3: cSound Architecture

Proper preservation of all the signals returned from the probe through the system electronics and software processing chain is crucial to present diagnostic quality ultrasound images to the users.

The processing chain starts with the shaping of the transmit pulses to obtain optimal axial resolution and penetration with minimal side lobes to reduce reverberations, shadowing and other acoustic artifacts. Receive amplification is performed followed by high-resolution analog to digital sampling and conversion.

The next step in the processing chain is the beamforming where data received from the probe elements are delayed and coherently summed. In conventional scanners, ultrasound beamforming is implemented with special purpose hardware (FPGAs, ASICs). Such ultrasound scanners can therefore only support a limited set of fixed and predetermined algorithms, and new algorithms typically require a lengthy hardware redesign. See left part of Figure 4.

In the cSound platform, all beamform processing is done in the back end of the system (in GPUs or CPUs), where RF data from each channel, from multiple consecutive and overlapping transmits, are received and temporarily stored in the "Local Big Data" channel memory as shown in right part of Figure 4. Then, advanced image formation takes place and the algorithms may vary depending on type of console, probe, application and mode. This processing is all software based and provides advantages in terms of flexibility and ability to quickly apply new and innovative algorithms, and also adapt them on the fly to the different modes of operation.

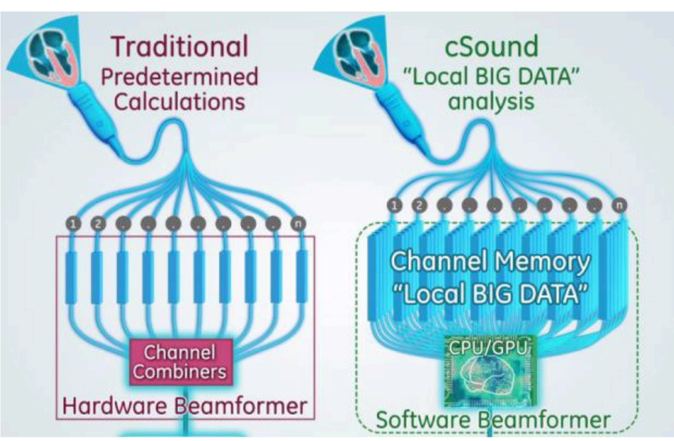

Figure 4: Hardware vs. Software Beamformer

The number of processing channels ("digital channels") is traditionally defined as a number proportional to the channel count that can contribute to the coherent beam sum. In the past, this was constrained by the hardware architecture of the beamformer and its associated processing circuits.

Now, with a software beamformer, there is no practical limit to the amount of channel data that can be stored and recombined into a single vector, so the number of processing channels is no longer a relevant limitation.

cSound architecture on Vivid E95

The back end in the Vivid E95 contains multiple GPUs. Unlike inexpensive gaming boards, the professional grade GPUs used in the Vivid E95 are designed to reliably handle 100% utilization over prolonged periods. These GPUs are the same type that one may find in artificial intelligence applications. One of the main benefits of the cSound implementation on Vivid E95 is that we can leverage new, more powerful and more power efficient GPUs as they enter the market. Each new generation of GPU brings new opportunities for implementing more powerful algorithms. It also means that we can offer the new features to existing customers by providing an upgrade kit containing new GPUs in addition to software.

First cSound based features and benefits

The cSound software beamforming architecture allows for development of features and functionality which has the potential to change the way cardiovascular ultrasound is used in the clinic. Below is a selection of some of the features and benefits enabled by this new platform, introduced in the first generation cSound based scanners from GE Healthcare launched in 2015.

True Confocal Imaging

In the so-called "channel processing," the RF data from each element is kept for further processing and can be used in the beamforming algorithms to achieve enhanced contrast as well as spatial resolution throughout the field of view, in combination with ultra-high frame/volume rates.

Confocal imaging, which previously was implemented by use of multiple focal zones originating from multiple transmits, is now available without loss of framerate and without the line artifacts usually present as a result of multi-line acquisition and/or multi-focus stitching. The need for a dedicated focus control is not needed with this technology.

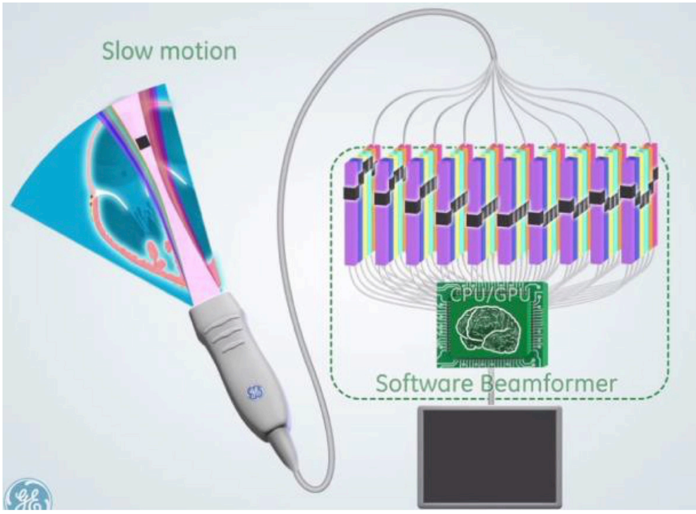

Figure 5: True Confocal Imaging

Key to this feature is the fact that the transmitted ultrasound beams have an hour glass shape which is wide laterally, both near and far, and receive data from within these wide transmit beams are collected and stored in the "Local Big Data" channel memory. Multiple consecutive transmit beams overlap in such a way that data for each and every pixel exists in many of the stored data sets in the channel memory. By intelligently processing, the algorithm is able to get an accurate real-time assessment of each pixel value. The end result is enhanced contrast and spatial resolution compared to conventional beamforming algorithms.

While this type of imaging without a conventional focal zone control is not unique to GE, cSound provides flexibility/versatility and easier adaptation to new algorithms than those solutions implemented in hardware/firmware. And since cSound is based upon commercially available processors, as they develop and are introduced into products, this may immediately transcend into increased processing power. Ultimately, enhanced image quality with the potential of increased diagnostic confidence and other benefits may arise from this.

Adaptive Contrast Enhancement

Adaptive Contrast Enhancement, or ACE, is the second feature enabled by the cSound architecture. True Confocal Imaging data for any given pixel is first stored into the "Local Big Data" channel memory. When all data from multiple consecutive transmits are collected and stored in the "Local Big Data" channel memory, the processor accesses this data, and makes two preliminary "internal" images.

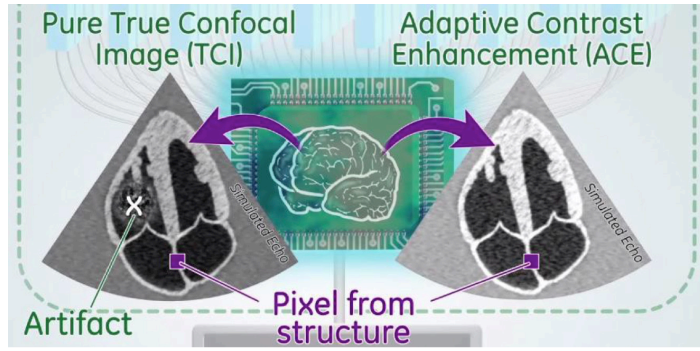

Figure 6: ACE (right) enhancing real structures

The left image is constructed using the TCI algorithm as described previously. On the right image, the same data is accessed. However, with the ACE algorithm the pixel is observed over a short period of time to determine whether or not data for the pixel originates from a "real" structure. In this example from the atrial septum, the pixel originates from a "real" structure. If the algorithm makes the assessment that the data is real, it enhances the pixel intensity. If it is noise or artifacts, like in this example inside the right ventricle, the algorithm reduces its intensity. With the high degree of parallel processing available, this assessment is done simultaneously for all pixels.

The two internal images are combined to achieve a high contrast resolution image (Figure 7). Compared to the traditional display image on the left, cSound's TCI and ACE combined image on the right has greater clarity with enhanced spatial and contrast resolution throughout the field of view.

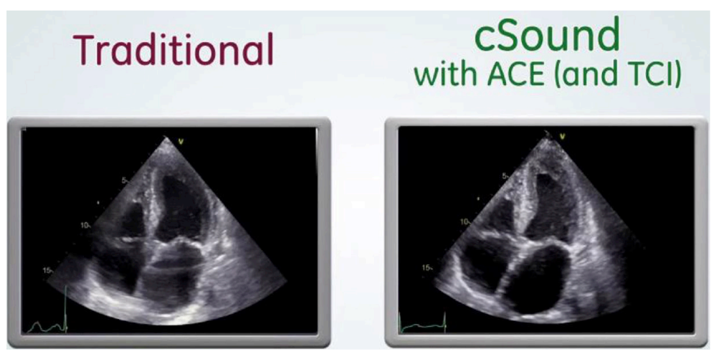

Figure 7: The combined effect of TCI and ACE compared to traditional beamforming

The cSound architecture benefits all probes and applications including adult cardiac (2D and 4D, TTE and TEE), pediatric cardiac, fetal/obstetrics, abdominal, pediatric, breast, thyroid, adult and neonatal cephalic, peripheral vascular, musculoskeletal and urology/prostate.

GE Healthcare Quantification Innovations

1991-1995

- AMM (offline)
- TVI

1996-2000

- Real-time AMM
- Strain
- Strain Rate
- Displacement
- Tissue Tracking
- Q TVI
- Quantitative Contrast Imaging
- Q-Stress (TVI based)

2001-2005

- Strain Imaging
- TSI (2D)
- 2D Strain
- Triplane EF
- 4D TSI
- IMT

2006-2010

- Advanced TSI
- AFI
- 4D Auto LVQ

2011-2015

- Tri-plane AFI
- AFI for TEE
- 4D Strain
- 4D LV Mass
- 2D Auto EF
- 4D Auto LVQ for TEE
- Multilayered Strain
- Peak Strain Dispersion
- AFI Stress
- 4D Auto AVQ

2017

- Myocardial Work
- Cardiac Auto Doppler
- 4D Auto MVQ
- 4D Auto RVQ

Figure 8: GE Cardiovascular Ultrasound's History of Quantification

Raw data format

Historically the Vingmed scanners, prior to the GE Vivid product line introduction in 2000, have always acquired and stored data in a specific raw data format which has enabled onboard as well as after the fact post processing capabilities otherwise impossible. This flexible and innovative format (storage of pre-scan converted data) has enabled development of utilities with high clinical value, such as Anatomical M-Mode — creating an angle corrected M-Mode display from a 2D dataset — and baseline shift in color for PISA measurement done on color loops acquired without baseline shift. The raw data format has also been instrumental in GE's successes in the area of quantification — from tissue Doppler based techniques (TVI, Strain, Tissue Tracking, TSI) in the late 1990's and early 2000's legacy scanners, to 2D speckle tracking (2D Strain and AFI) and 4D speckle tracking (4D Strain) introduced later on the Vivid E9 platform.

In the progression of platforms for the above-mentioned scanners, more and more image acquisition, image processing and display processing were moved from dedicated hardware to software. Over the years this has resulted in an increase in the ability to perform more and more advanced algorithms for all steps in the data processing chain.

It is important to understand that the format of the raw data has not fundamentally changed with the advent of the cSound platform. The huge amount of data in the "Local Big Data" channel memory previously mentioned is discarded after image reconstruction, so the stored raw data file sizes are approximately of the same size as before. A slight increase may however occur, should the user take full advantage of the higher spatial and temporal resolution enabled by cSound.

Second generation cSound based features

The second release of the cSound based products including Vivid E95 was launched in the summer of 2017. In this release, there was continued focus on expanding the software beamforming algorithms to further enhance 2D image quality, and in addition the platform was utilized to enhance 2D color performance.

Texture (Enhancement)

As described previously in this paper, ACE improves image clarity – especially on difficult to scan patients. However, there are cases where more information can be provided by processing the channel data in a different way. To address these cases, we developed a non-linear beamforming technique called Texture. Texture is a further development of ACE that aims specifically at providing additional information from within the myocardium. The figure below illustrates how Texture may provide additional information. ACE was used to generate the image on the left side while Texture was used to generate the image on the right side. The images are taken from a known amyloidosis case.

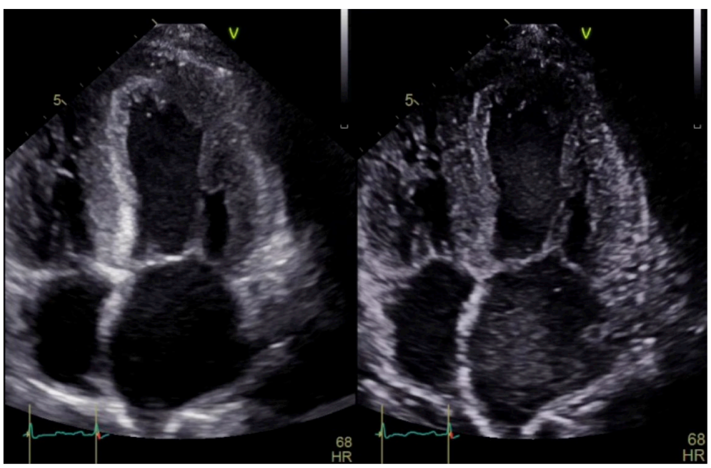

Figure 9: Texture (right side) vs ACE (left side) in case of amyloidosis

Color Flow (Enhancement)

The cSound platform has been used to enhance color specificity spatially and temporally by applying a new transmit algorithm as well as an adaptive color detection algorithm combined with new visualization maps and smoothing algorithms. All with the purpose of potentially offering a quicker diagnosis with higher confidence. See Figure 10 for a comparison.

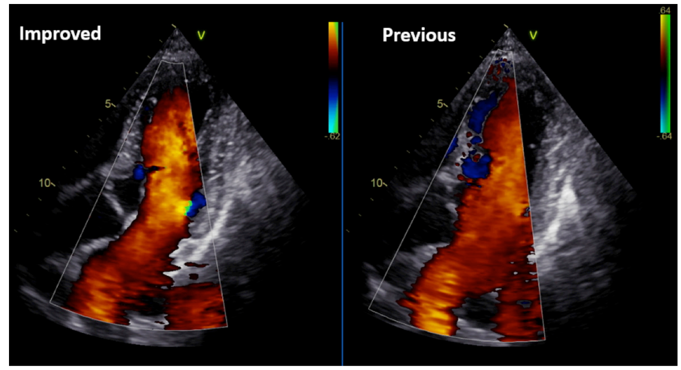

Figure 10: Enhanced color flow visualization

Visualization with cSound

Blood Speckle Imaging (New)

Blood flow imaging using conventional color Doppler technology is limited due to Doppler angle dependency (display of only radial velocities) and aliasing (velocity scale is limited by the pulse repetition frequency – “Nyquist limit”). Blood Speckle Imaging (BSI) is a novel blood flow visualization technique overcoming both limitations in conventional color flow imaging. BSI is based on tracking of speckles generated by the moving blood cells, from one frame to the next using a “best match” search algorithm. This allows direct assessment of two-dimensional blood velocity vectors, without requiring injection of contrast agent, and without the mathematical assumptions of approaches based on conventional color Doppler. Typical acquisition framerates for BSI are in thousands of frames per seconds (FPS) range, but are reduced to 400-600 FPS on the display (depending on the size of the Region of Interest (ROI)). This ultrahigh framerate acquisition is obtained using a plane wave imaging technique. This method is based on utilizing broad transmit beams allowing multi-line acquisition of a much higher degree than used previously.

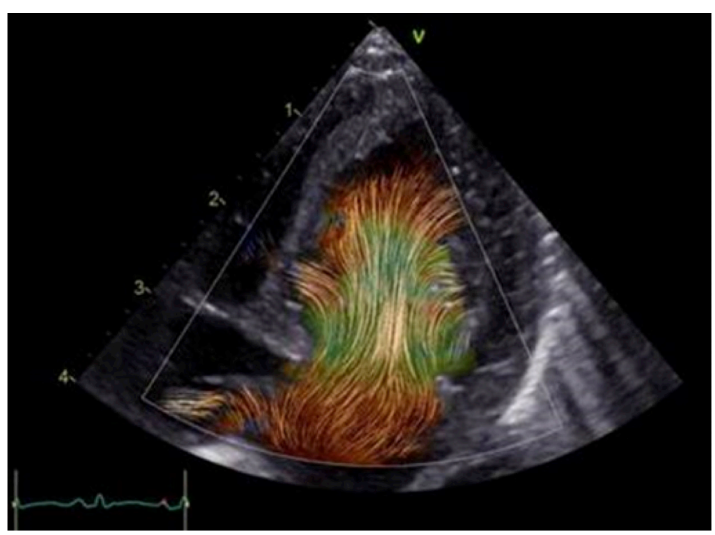

Figure 11: Blood Speckle Imaging

4D

The 4D processing chain has been streamlined in order to do real time spatial processing, enabling development and implementation of advanced algorithms like 4D Clarity and HD*live*.™ 4D Clarity provides crisp images with excellent resolution and detail level.

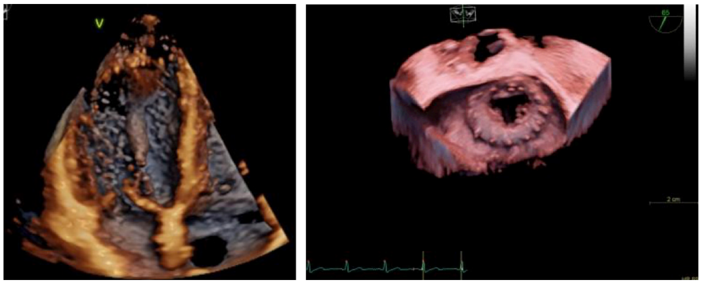

Figure 12: 4D Clarity, HD*live* and cSound acquisition provide high quality TTE and TEE images

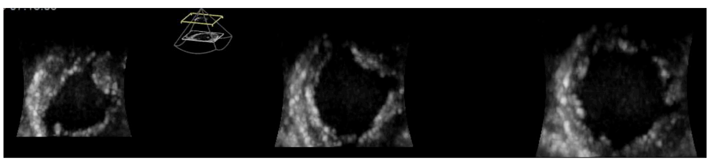

Figure 13: 4D Clarity and cSound acquisition provide high quality extracted slices

HD*live* (Enhancement)

HD*live* generates an amazingly realistic visualization of the human heart through advanced illumination, shadowing and reflection algorithms. HD*live* can be used to enhance 4D depth perception during image-guided interventions or in the echo lab for regular TEE or TTE imaging. The technology behind this feature is extremely resource demanding, and is enabled by the cSound platform and its powerful processing capabilities, whether during high volume rate single- or multi-beat 4D imaging.

Basically, HD*live* is a real-time simulation of light travelling through tissue giving the user a much more realistic perception of the shape of valves and other clinically important structures. This is shown in Figure 14 where a catheter is visualized and illuminated by a light source located at approximately 2 o'clock, casting a shadow on the wall behind it. Also notice how the surfaces reflect light and in combination with the light scattering through tissue create a three dimensional perception even when shown in this two dimensional picture. The HD*live* algorithm now provides enhanced image quality for certain viewing directions (Figure 15). The HD*live* algorithm contains several sub-features that are described in this section.

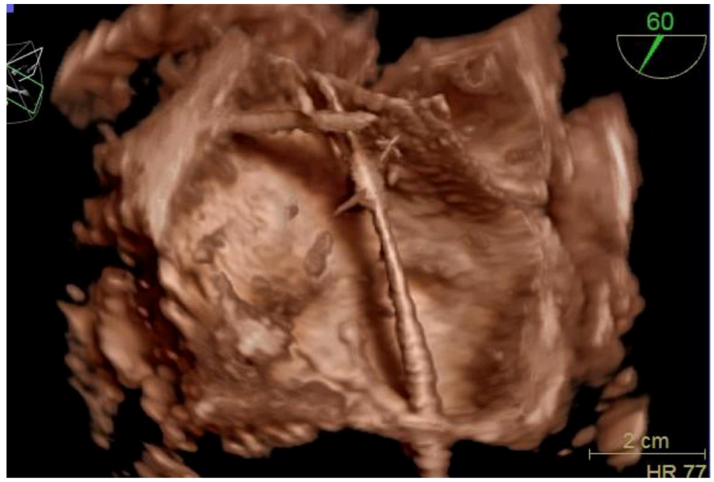

Figure 14: HD*live* visualizing a catheter during an interventional procedure

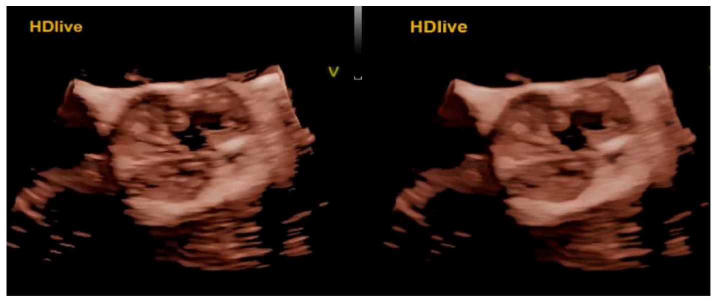

Figure 15: Example of enhanced (right) vs previous (left) HD*live* image of an aortic valve

Depth coloring

Depth coloring is well known from the past and frequently used for rendering volumes in cardiac applications (both with TTE and TEE probes). Depth coloring enhances depth perception but does not give a lot of detail.

Direct, indirect and ambient lighting

Direct lighting is applied to the scene to create sharp shadows via monochromatic light attenuation. These shadows help with perception of small details in the image. The image may however become quite dark in several regions if the light attenuation is very strong. Indirect lighting is applied to create soft shadows via diffuse chromatic light attenuation. This part of the algorithm simulates light scattering effects creating soft colored shadows. Ambient light is added to the scene to lighten up the dark parts of the image. Figure 16 illustrates a combination of direct, indirect and ambient lighting. In the example, light attenuation for the blue color is lower than other colors resulting in bluish diffuse shadows.

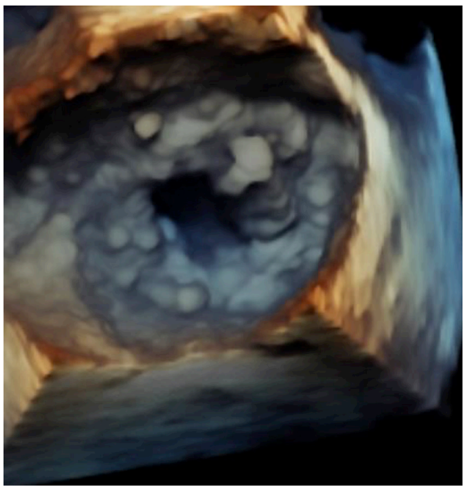

Figure 16: Direct, indirect and ambient lighting

Specular and diffuse reflections HDR processing

Specular and diffuse reflections are added to brighten up details (Figure 17). These are simulating light reflections from the light source hitting the surfaces and bouncing back towards the eye. Both depend on the light direction, the local surface orientation (normal) as well as the viewing direction. Similar to what is implemented in state-of-the art cameras, HDR (High Dynamic Range) processing is finally added to the image. This step greatly enhances local contrast in shadow regions visually extending the dynamic range of the rendered image.

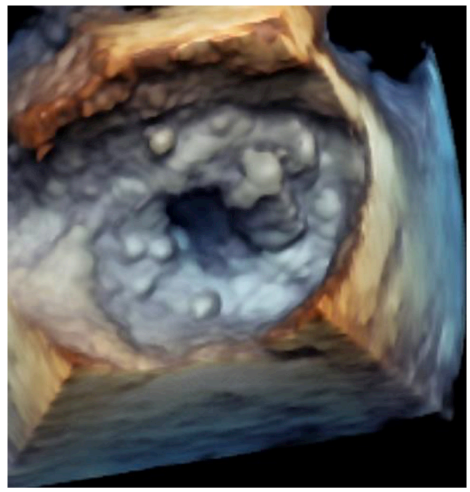

Figure 17: Adding specular and diffuse reflections and finally HDR processing

Moving the light source

By moving the light source (easily controlled by a rotary) the shadows and reflections are adjusted interactively. Below illustrates what happens when the light source is rotated so that the light comes from above (left image) and below (right image).

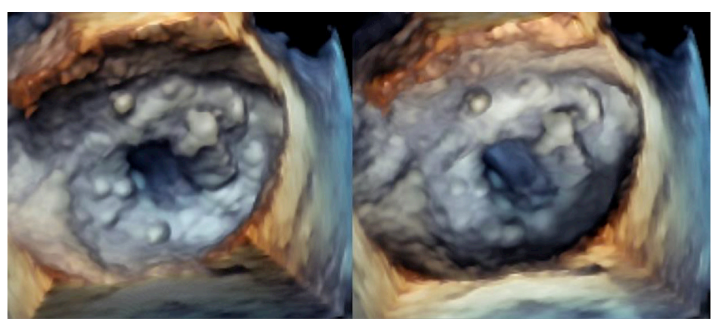

Figure 18: Moving of the light source may enhance certain details

Features in development

Enhanced 4D image quality*

As previously mentioned, the Vivid E95 contains professional GPUs that perform the per-channel calculations of the beamforming. These GPUs can be replaced as new and more powerful designs become available. Increased computational performance enables, for example, enhanced 4D image quality and volume rates through use of more powerful software algorithms. As an illustration, we have included an example of a test with a state-of-the-art (July 2017) high end GPU. The real-time volume rate ("Single Beat Imaging") of our 4D TEE probe has been increased by a factor more than 5, while retaining a similar image quality as the base line.

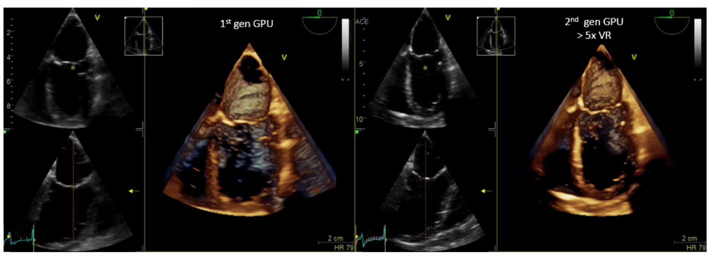

Figure 19: Potential for greatly improved volume rates with 6Vt-D

Real time image classification*

"Deep learning" is a hot topic and particularly in medical imaging. The GE Healthcare Cardiovascular Ultrasound business strongly believes deep learning algorithms will be instrumental in improving workflow efficiency in future ultrasound scanners. With extensive on-board computational resources, Vivid E95 is well prepared for future deep learning-based features. It is beyond the scope of this paper to go into details about deep learning in general, but we will give one imaginable example here: automatic cardiac view detection. This is one out of several potential building blocks for future deep learning-based features. Our initial results indicate that a deep convolutional neural network can be trained to reliably distinguish between standard apical and parasternal views and in real time.

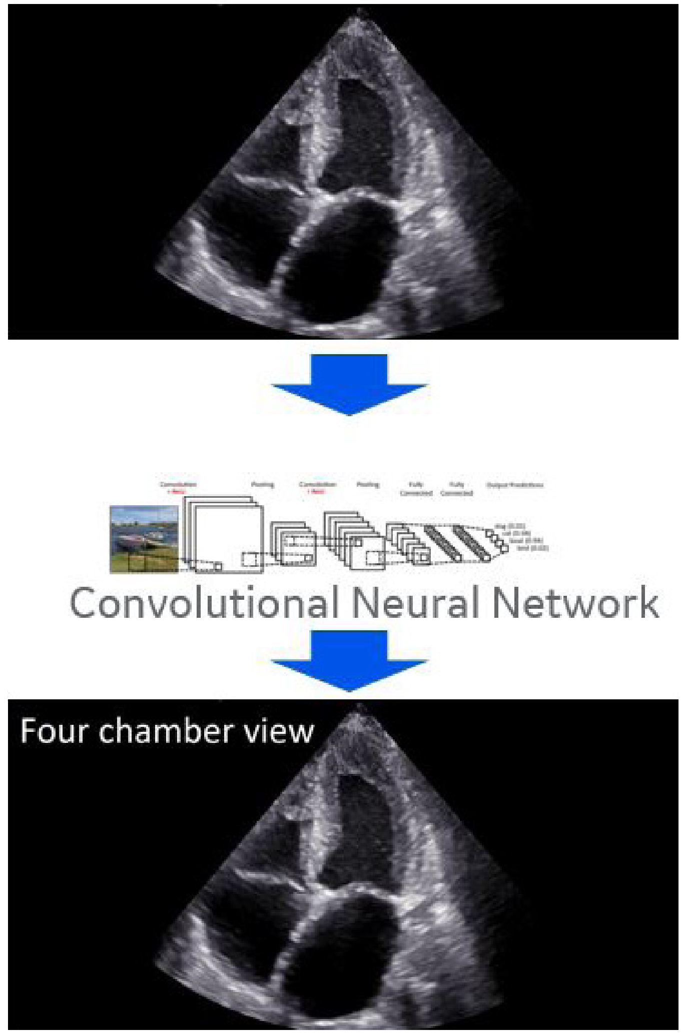

Figure 20: Illustration of deep convolutional neural network

*Note: Technology in development that represents ongoing research and development efforts. These technologies are not products and may never become products. Not for sale. Not cleared or approved by the U.S. FDA or any other global regulator for commercial availability.

Summary

In many ways, the new cSound platform is taking our raw data to the next level, by providing a magnitude of data available for real time processing compared to what is available in the previous platform. As computer technology evolves (Moore's law), so will the processing power of the cSound platform and its imaging capabilities.

In the first generation cSound based systems we focused on:

- Developing new leadership scanners with 2D (Vivid E80/Vivid E90/Vivid 95) and 4D (Vivid E95) image quality and quantification tools that may enable the user to diagnose more patients than before with higher diagnostic confidence
- Developing a new level of high end scanners (Vivid S60/Vivid S70) with the performance of current leadership systems, and further enhancing the ease of use and portability of its predecessor

In our latest software release we have focused on:

- Further enhancing basic image quality with new features such as "Texture"
- Further enhancing 3D image quality with an enhanced version of HD*live*
- Developing a completely new way to visualize complex blood flow patterns (BSI)

We have also given a bit of insight into what the GE Healthcare Cardiovascular R&D team is working on:

- Significantly improving 3D image quality
- Automatic cardiac view detection using deep learning

What the future will show in addition is unknown, but as you partner with GE on the cSound path, be assured that you are on a fast-moving track that is always striving towards better and better patient care.

Imagination at work

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