Description and implementation of the Supersonic Shear Imaging method on the Verasonics research system

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Abstract. The method of shear wave elastography Supersonic Shear Imaging is presented. A scheme for implementing this method on the Verasonics research system and an algorithm for processing and outputting data as an elasticity map are developed. Physical modelling was carried out with a CIRS model 049 elasticity phantom on the Verasonics research system using SSI and SWEI methods, and on the Supersonic Aixplorer ultrasound system. The results were compared and shown the method presented to be applicable for the research system.

1. Introduction
There is a wide range of pathological processes that change the material properties of organ tissue, such as the liver, mammary gland, thyroid gland, skeletal muscle, pancreas, spleen, kidney, etc. Various processes, such as inflammation, fibrosis, edema, and cancer formation cells - all this contributes to a change in the material properties of organs, since the components of the organs change on a microscopic scale, which leads to changes observed on a macroscopic scale (from micrometers to centimeters). Over the past 25 years, scientists have been working on methods for displaying the elastic properties of organs and tissues in the body, elastography. Currently, studies on the problem of detecting malignant tumors use the Supersonic Shear Imaging (SSI) elastography method [1].

2. Supersonic Shear Imaging method
Supersonic Shear Imaging is a new method for determining the elastic properties of a tissue under study, which uses some features of previously presented ultrasound diagnostic techniques, in particular Shear Wave Elasticity Imaging (SWEI) [2]. Several sources of shear wave propagation are excited in a medium. To do this, several focusing beams are triggered sequentially into the medium, which are characterized by a shift of the focusing point in depth, creating a moving source of shear. The main condition for creating this source is its movement with a greater velocity than the shear wave one in the medium, i.e. “Mach number” \( M > 1 \). Formed shear waves, interfering with each other along the formed “Mach cone”, form two quasi-plane waves propagating in different directions.

Having a large amplitude compared to the usual shear wave generated in the SWEI method, a quasi-plane wave travels a sufficiently large distance and penetrates various objects in the medium before damping, and its shape allows it to be evenly distributed over the entire depth of the studied region. The "Mach number" is responsible for the angle at which a quasi-plane shear wave propagates. With the increase of this indicator, the angle will begin to tend to with respect to the direction of wave propagation. In this regard, separate modes of this method are even distinguished based on the value of
the number $M$ (Mach 3, Mach 4, Mach 5, Mach 10, Mach -3). Separately, it is worth noting the operation mode of Mach -3, in which beginning the formation of the cone begins from the deepest point. However, the most frequently mentioned modes in the literature are Mach 3, in which the ratio of the focus shift velocity to the shear wave one is 3, and Mach 10, in which this ratio is 10.

After the generation of quasi-plane shear waves, the process of recording their propagation in the medium is carried out using the Ultrafast Imaging method. In SSI, this technique is used for several purposes at once. After each start of the focused beam, a set of ultrafast frame rate imaging beams is launched. Based on the data obtained by them, conclusions are drawn about the formation of the Mach cone. The main pack of imaging beams, in which the number of beams can reach 100, starts after pushing sequences are completed. It registers their further distribution, and on the basis of the recorded data, further processing and output of the results on the elasticity of the tissue in the selected area are performed.

3. Implementation of the SSI method on the Verasonics research system

The Supersonic Shear Imaging method was implemented on the Verasonics research system in the MedLab laboratory of the Radiophysics Faculty of Lobachevsky State University of Nizhny Novgorod [3]. The Verasonics research system is an universal ultrasound diagnostic device designed for prototyping and debugging various algorithms of medical acoustics. It has the ability to widely vary the parameters of ultrasonic waves and program them depending on the tasks and objects of study. Received echoes are recorded by the device and are available for post-processing in the form of arrays of numerical data. The whole scenario of sending pulses, receiving and processing data, building an image is programmed by the user in MATLAB [4].

3.1. Implementation of the formation of quasi-plane shear waves

When implementing the SSI method on Verasonics, 5 focusing pulses were taken to form a quasi-plane shear wave. The depth distance between the focus points was chosen 5 mm. The optimal difference between the shift velocities of the focus of the shift ($V_f$) and the shear wave ($V_{sh}$), which was equal to 2.76 m/s when developing the method, was chosen equal to 3 ($M = 3$).

The classical scheme on Verasonics made it possible to reliably store the data on the propagation of each individual shear wave due to the presence of a burst of 5 imaging pulses after the first 4 focusing
pulses. However, they led to large intervals between pushing beams, which gave a very small difference between the velocities of the focus shift and the shear wave in the medium \( (V_f = 3.57 \text{ m/s}, M = 1.5) \). It was found that due to this factor, when measured in media with higher elasticity, there is a probability that quasi-plane shear waves will not form, which is the basis of the whole technique. In this regard, this scheme was modified. Instead of a burst of beams, only one image was launched between the focusing ones. This made it possible to save a part of the data on the propagation of each individual shear wave, as well as to increase the difference between the velocities of the focus shift \( (V_f = 8.3 \text{ m/s}) \) and the shear wave in the medium, which began to reach the maximum value equal to \( M = 3 \). This is sufficient for the formation quasi-plane shear waves and there is a margin when measuring in more elastic media.

![Figure 2](image.png)

**Figure 2.** Scheme of SSI method implementation on Verasonics research system

For the cases of measuring objects in which the medium has a higher elasticity index (for consideration, a medium with a Young's modulus of 48 kPa or 4 m/s was taken), the scheme of pulses sent to the medium was modified. In this scheme, the intermediate imaging pulses, which register the formation of the Mach cone, have been removed. This gave an opportunity to increase the focus shifting velocity \( (V_f = 12.5 \text{ m/s}) \), which makes it possible to obtain \( M = 3 \) when working with media in which the shear wave velocity is 4 m/s, and for less elastic media the Mach number can reach \( M = 6 \), which affects the angle at which the quasi-plane shear waves propagate. It is proposed to control the formation of the cone in this scheme due to its final shape, which is recorded by the first imaging pulse.

A set of imaging pulses is used to register the propagation of quasi-plane shear waves. The circuit was taken as a basis, which was already used on the Verasonics research system when implementing the SWEI method on it \([5]\). 200 μs is a sufficient delay between pulses for high-quality tracking of the dynamics of wave propagation in the medium. However, during the SSI implementation, it was revealed that 19 imaging pulses are not enough to fully track the propagation of quasi-plane shear waves in the area under study. In this regard, the number of imaging pulses was increased to 29. With this sequence of pulses, the system can record changes in the medium due to the propagation of quasi-plane shear waves for 6 ms. At \( V_{sh} = 2 \text{ m/s} \), this makes it possible to increase the area under study from 1 cm, which was used when calculating the shear wave velocity by both its components and its visualization in the SWEI method, up to 3 cm with the inclusion of the cone formation region.

3.2. **Processing of data obtained in the course of the SSI method**

The primary processing of the results obtained using the SSI method for receiving data on the displacement of points in various coordinates of the medium area under study is similar to that used in the SWEI method. The offset is calculated by correlating one of the imaging pulses with the reference. By the shift of the peak of the correlation curve relative to zero, one can determine the wave lag caused by the displacement of the medium. When processing the data obtained by the SSI method on
Verasonics, it was necessary to take into account the appearance of imaging pulses, which are responsible for registering the formation of the cone.

3.2.1. Algorithm for visualizing the formation and propagation of quasi-plane shear waves. The first algorithm written for the final data processing for the SSI method is the visualization of the formation and propagation of quasi-plane shear waves. This algorithm is based on the shear wave propagation script in the SWEI method, but has several characteristic differences.

First, since the quasi-plane shear wave has an increased amplitude compared to the simple one triggered by the SWEI method, it propagates over long distances. In addition, the difference between the first focus point and the last one in depth is 20 mm, so it is necessary to increase the grid not only in width, but also in height (depth). The final grid size for visualizing the waves was 101 × 51 cells (when converted to units of measurement, it will turn out to be 30 mm in depth and 15 mm in width).

Secondly, Verasonics, when using the SSI method, records data from 33 imaging pulses, excluding the reference one. Processing the results taking into account the size of the new grid leads to a significant increase in the algorithm’s runtime.

To optimize the algorithm, the number of imaging pulses taken into account was reduced to 11. During processing, only pulses scanning the medium during the formation of the Mach cone will be taken into account, and after the formation of quasi-plane shear waves and the start of their propagation, every third imaging pulse from the main burst will be taken into account.

![Figure 3. Visualization of the formation and propagation of quasi-plane shear waves](image)

The proposed algorithm makes it possible to judge the correctness of the formation of quasi-plane shear waves. Its use in the first implementation scheme of the SSI method on the Verasonics research system showed the model’s inadequacy, since the visualization clearly showed the absence of the phenomenon of the formation of quasi-plane shear waves, and only the propagation of separately formed shear waves was observed.

3.2.2. Algorithm for creating an elasticity map based on measured data. A separate algorithm was written to process the data when using the Supersonic Shear Imaging method on the Verasonics research system and to obtain the final result in the form of identifying elastic characteristics in the object under study, in the form of shear wave velocity or Young’s modulus. The interface of the Supersonic Aixplorer expert system, namely its elasticity map, was taken as a basis from the point of view of the visual presentation of the result.

In this case, an algorithm was used to obtain a grid that stores in its cells the data on the displacement at each point of the study area, which is used to visualize the propagation of a shear wave and a quasi-plane wave. To create an elasticity map, the grid size is increased to 101 × 101 cells or 30 × 30 mm. It should be noted that all imaging pulses (frames) from the burst recording the propagation of a quasi-
plane shear wave are taken into account. However, the pulses recording the medium at the time of the formation of the Mach cone are ignored.

At each point through which the quasi-plane shear wave has passed, the displacement function has a clearly pronounced maximum at a certain moment in time, corresponding to the time of arrival of the wave front in a given section of the region under study. Comparing the coordinates of a cell along an axis parallel to the propagation axis of a quasi-plane shear wave with the time of arrival of the wave at a given cell, and knowing the same parameters for a neighboring cell, it is possible to calculate the velocity of the wave propagation in a given section. Theoretically, 2 cells are enough for these purposes, but in order to reduce the effect of noise, it is proposed to take into account more of them.

In the course of writing the algorithm, it was proposed to take at least 3 cells with the main central one. In this case, the result obtained in the form of velocity and the Young's modulus recalculated from it would be attributed to the 2nd (central) cell. This choice is due to the influence of the medium on the passage of the wave at a given point in comparison with the previous and subsequent ones. The proposed scheme allows to simplify the processing algorithm when calculating the value of Young's modulus at the edge cells. Combinations of 3, 5, 7 and 9 cells were tried. As a result, the optimal value is 5 cells with the main central one.

As a result, an algorithm was written that produced an array of 101 by 101 cells at the output, each of which contains the value of Young's modulus at a given cell. Using the MATLAB software environment allows to get a map of the distribution of Young's modulus in the area under study, depending on the objects in it. Young's modulus was chosen as the final numerical result, since its values, depending on the object under study, can vary in values from 0 to 100 kPa or more, and not the shear wave velocity, the values of which can vary from 1 to 20 m/s.

![Figure 4](image)

**Figure 4.** Elasticity map derived from the SSI method on Verasonics research system

### 4. Measuring Calibrated Phantom CIRS Model 049 by SSI method

To test and debug the implementation scheme of the Supersonic Shear Imaging method on Verasonics, as well as the developed algorithm for obtaining the elasticity map based on the results of the method, a series of experiments was carried out using the calibrated phantom CIRS MODEL 049 ELASTICITY QA PHANTOM - SPHERICAL. This phantom is a model of soft biological tissue made from Zerdin, containing inclusions in the form of spheres of different radii with a certain value of Young's modulus. When measuring this phantom, several points were revealed when working with the SSI method.

Its main feature is the need to aim not at the object itself, as it happens in the SWEI method, but away from the object. This is due to the fact that when processing the results in the central area of the elasticity map, a so-called blind zone appears, which corresponds to the dimensions of the Mach cone we are
It appears due to the fact that our algorithm does not take into account the first 4 imaging pulses, which are recorded by the medium at the moment of the formation of quasi-plane shear waves. If the propagation of waves starts directly from the object under study, then in this case, part of the object (and possibly all, depending on its size) will be covered by the blind zone, which means that part of the data about it is lost.

### Table 1. Results of measurements of the calibrated phantom CIRS MODEL 049 on the Verasonics research system using the SWEI and SSI method and on the Supersonic Aixplorer ultrasound system

| Type   | Verasonics, SWEI | Verasonics, SSI | Supersonic Aixplorer |
|--------|------------------|-----------------|----------------------|
|        | V, m/s           | E, kPa          | E, kPa               |
| Background | 2.63             | 20.72           | 19.3                 | 20.59             |
| I      | 1.46             | 6.36            | 8.51                 | 7.05              |
| II     | 1.83             | 10.02           | 11.52                | 11.20             |
| III    | 3.25             | 31.69           | 31.37                | 33.19             |
| IV     | XX               | XX              | 65.17                | 61.18             |

During the work with the phantom, using the SSI method, 4 nesting-spheres of different types were measured. The results are shown in Table 1. It should be noted that the result is shown immediately in terms of Young's modulus, which differs from the SWEI method. To check the correctness of the results obtained, the measurements of the calibrated phantom are given using the Verasonics research system using the SWEI method, as well as using the Supersonic Aixplorer expert system. The results obtained using the SWEI method are given in two dimensions, shear wave velocity and Young's modulus, due to the initial result obtained in the form of velocity and its subsequent conversion into Young's modulus. It is also worth noting that when measuring on the Verasonics research system, the SWEI and SSI methods were applied to the ultrasonic transducer elements with one voltage value, 50 V.

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