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Clipping removal in Synthetic Aperture Imaging

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ABSTRACT

Clipping artifacts impact the image quality and diagnostic accuracy in ultrasound imaging. This study introduces a post-processing technique designed to eliminate clipping in ultrasound scans acquired using synthetic aperture ultrasound systems (SAUS). It is hypothesized that the proposed method can effectively masks out clipped signals while preserving non-clipped contributions and without a significant loss of image quality.

A phantom and an in-vivo rat brain scan were used to test this hypothesis. The analysis of the phantom data showed that the proposed method can be applied to remove mild levels of clipping without a significant loss in contrast and resolution. In fact, when up to 30% of the data was clipped, the loss in resolution after applying clipping removal was lower than 2.5% and the contrast decreased less than 7.9%, when compared with the original non-clipped image.

In-vivo results, on the other hand, demonstrated that applying the proposed algorithm effectively removes clipping artifacts while preserving the underlying information. Additionally, it enhances the image's dynamic range by approximately 12%, when compared with the clipped data.

Keywords: Clipping, Artifact, Skull, Synthetic Aperture, Ultrasound, Brain, Transcranial Imaging, Power Poppler, PD, Super-Resolution, SRI, SURE, Contrast-free

1. INTRODUCTION

Clipping is the truncation of a signal's value when it exceeds the system's maximum limit, resulting in a loss of information. In ultrasound systems, clipping is especially common in areas with significant variations in tissue density, such as the liver and bowel, or when imaging strong reflectors, such as the skull on transcranial brain scans or calcifications in the carotid artery.

Clipping not only degrades image quality by introducing artifacts and distortion, but also reduces the contrast of the image. Consequently, clipped images can be difficult to interpret for medical practicioners and methods for preventing or eliminating clipping are needed in medical image analysis.

Several techniques are used to avoid clipping, for instance, the gain of the system can be reduced to decrease the amplitude of strong reflectors. Images can also be acquired at different acoustic power levels and then combined to create high dynamic range images (HDR)[1], but this reduces the frame rate of the system. However, in some cases clipping is unavoidable, and methods for reducing the resulting artifacts become necessary. In these cases, a perfect restoration of the signal is not possible because part of the signal is lost, but post-processing methods can prevent clipping from significantly altering the image.

Most existing clipping removal techniques replace clipped signal values with estimated values, e.g., using time- or frequency-domain interpolation [2][3][4], or deconvolution [5]. In contrast, this work introduces a technique that only uses values already present in the recorded signals and does not add any estimated values.

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In ultrasound systems such as plane wave systems and synthetic aperture ultrasound systems (SAUS), each pixel of an image is created by combining signals from multiple plane waves or virtual sources. In SAUS [6], specifically, the transmission pulse is generated by a subset of elements (driven by a virtual source), and the echoes from the imaged object are received from all elements of the transducer. Consequently, each pixel is the coherent sum of echoes from multiple receivers on multiple emissions (total number of signals that contribute to a pixel: N_e x N_l, being N_e the number of emissions and N_l the number of elements). Therefore, if at least one of these signals is not clipped, clipped signals can be discarded while preserving the non-clipped information for that pixel. This paper hypothesizes that clipped signals can be removed from the image without a significant loss of image quality.

A single wire phantom and a rat brain are imaged to test this hypothesis, and the resolution, contrast, artifact presence and effective dynamic range will be compared before and after clipping removal.

2. MATERIALS AND METHODS

2.1 Materials

Ultrasound scans were performed using a Verasonics Vantage 256 research scanner (Verasonics, Inc., Kirkland, WA, USA) and a 168 element 10 MHz GE L8-18iD linear array probe (GE HealthCare, USA). An interleaved recursive synthetic aperture sequence with 12 virtual sources was used to acquire the images.

All processing was performed in Matlab 2021b (MathWorks, Massachusetts, USA).

2.2 Methods

2.2.1 Clipping Removal Algorithm

The proposed clipping removal algorithm operates on the principle that each pixel is created by combining various received signals. If at least one of these signals is not clipped, it should be possible to remove the clipped signals while preserving the underlying information for that pixel. However, if most signals show clipping, too much information will be removed by the algorithm. The diagram in the Fig. 1 provides a simplified overview of the method.

The clipping removal algorithm works in two steps:

1. Signals are classified as clipped if their amplitude reaches the system's maximum limit at any point.
2. Clipped signals are set to zero, removing their impact before beamforming the image.

2.2.2 Single Wire Phantom

A single wire phantom was used to evaluate how the proposed method affects the resolution (lateral and axial) and contrast of the images. A 5-second scan was performed, ensuring that clipping was avoided during the process.

After data acquisition, clipping was artificially introduced in the data at various levels (5%, 30%, 65%, 90%) by setting threshold limits on the amplitude of the signals. For example, to introduce 5% of clipping into the data, an amplitude threshold was set such that 205 out of the 4032 received signals (N_e x N_l) were clipped ($205 \times 100 / 4032 = 5\%$).

After introducing clipping, the clipping removal algorithm was applied. The PSF, resolution and contrast of the resulting images after clipping removal and the original non-clipped image were compared.

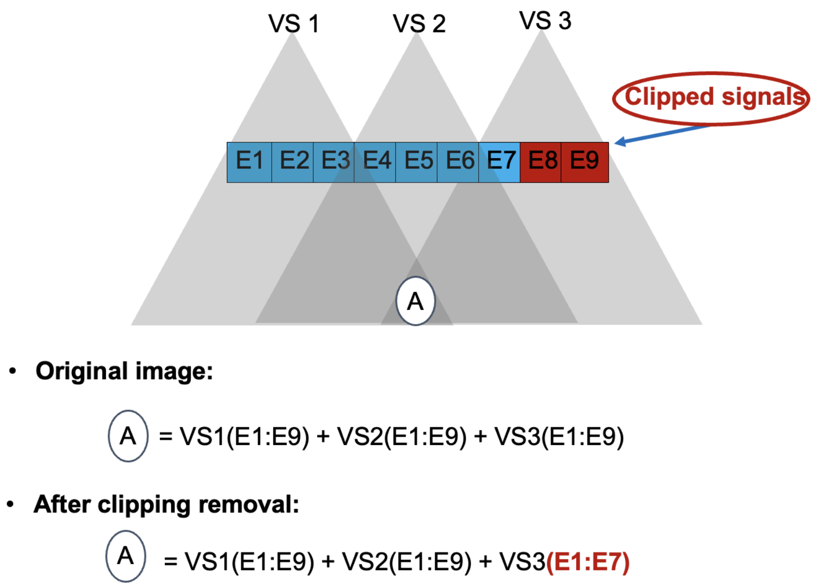


Figure 1: Illustration of the Clipping Removal Algorithm. A SAUS with 9 elements and 3 virtual sources is scanning object A. The received signal from 2 elements (E8 and E9) after the emission of virtual source 3 is clipped, and consequently, it is detected and masked out by the clipping removal algorithm: these two signals do not contribute to the image of object A. However, the rest of received signals do provide information about object A.

2.2.3 Animal Model

An additional experiment was conducted on a healthy male Sprague-Dawley rat (Age: 10 weeks, weight: 385 g) to evaluate the proposed method in-vivo. The procedures were carried out at the University of Copenhagen, adhering to all local ethical standards and in accordance with protocols approved by the Danish National Animal Experiments Inspectorate. The ethical guidelines of the University of Copenhagen align with the EU Directive 2010/63/EU for animal research.

The rat was anesthetized in a chamber with 5% Isoflurane delivered in 65% nitrogen and 35% oxygen. The anesthesia was maintained with an Isoflurane concentration of 1.5%–2% while performing a craniotomy and through the duration of the experiment. Normal body temperature (around 37 degrees) was also maintained, placing the rat on a heating pad and monitoring its temperature using a rectal probe thermometer.

A coronal plane of the rat brain was imaged for 2 minutes. The TGC of the scan was modified to allow a moderate amount of clipping.

Next, SURE images [7][8] of the rat brain were generated both before and after applying the clipping removal algorithm. Singular value decomposition (SVD) clutter filtering was applied, using the same singular values for both datasets. The two resulting images were then visually compared to confirm that the clipping artifacts were removed and that no previously available information was lost. Additionally, the dynamic range of the images was assessed for comparison.

3. RESULTS

3.1 Single Wire Phantom

In Fig.2 and 3, the PSF of both the original image and the artificially clipped images after applying the clipping removal algorithm, is shown, along with their resolutions and contrast.

These figures show that for 5% clipping removal, the resolution is maintained and the contrast is slightly improved. However, generally, as the percentage of clipped signals increases and is masked out, the contrast and resolution of the image decreases, as expected when removing signals that contribute to an image. Nevertheless, the changes in both resolution and contrast are not very significant when the level of clipping is low. Up to 30% of clipping removal, the loss in resolution after applying clipping removal is lower than 2.5% and the contrast decreases less than 7.9%, when compared with the original non-clipped image.

However, when clipping is above 60%, the resolution decreases by about 5.8% and the contrast by approximately 20%. Also, the shape of the PSF in this high levels of clipping removal starts to present asymmetries. Such distortions could lead to image artifacts, causing parts of the image to appear blurred or misaligned.

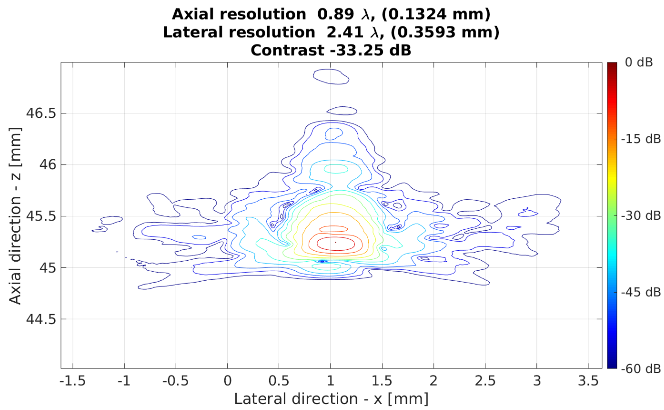
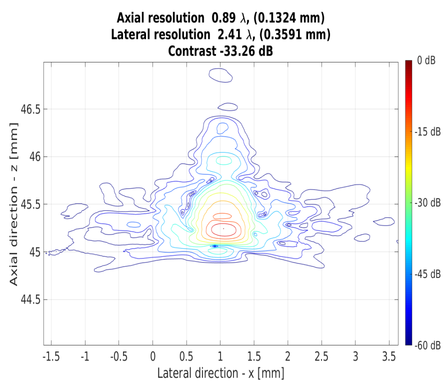
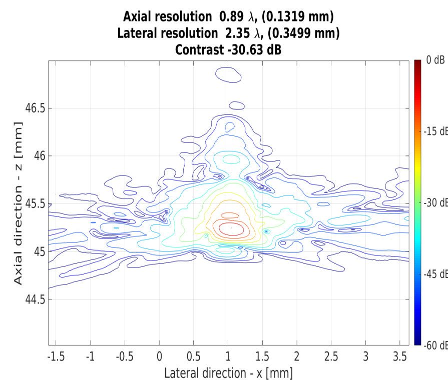


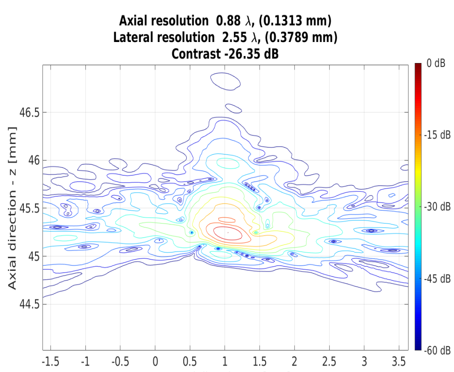
Figure 2: Original PSF



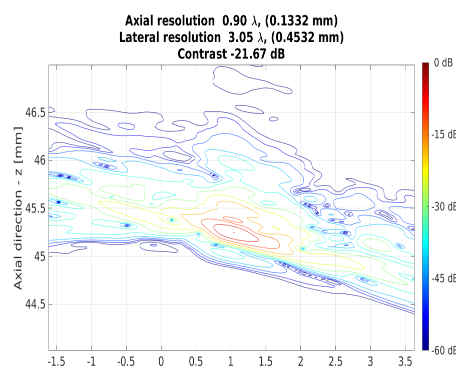
(a) PSF after 5% clipping removal



(b) PSF after 30% clipping removal



(c) PSF after 65% clipping removal



(d) PSF after 90% clipping removal

Figure 3: Point Spread Functions at various levels of clipping, ranging from 5% to 90%.

3.2 Animal Model

The method was then applied to the clipped rat brain data. Fig. 4 shows the original Power Doppler image of the rat brain, in which the clipped artifacts that need to be removed are highlighted in blue. A 5 seconds-SURE image of the rat brain was created before clipping removal and is displayed in Fig. 5a. A clipping artifact in the shape of curved lines can be observed very clearly in the same area highlighted in Fig. 4.

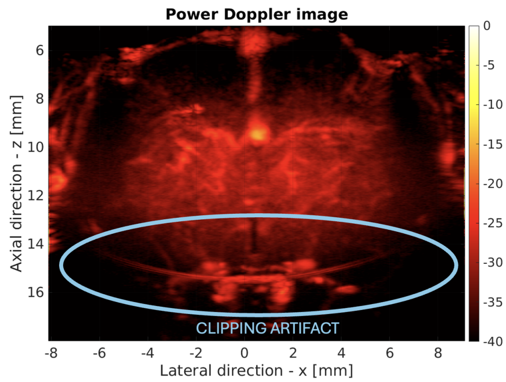
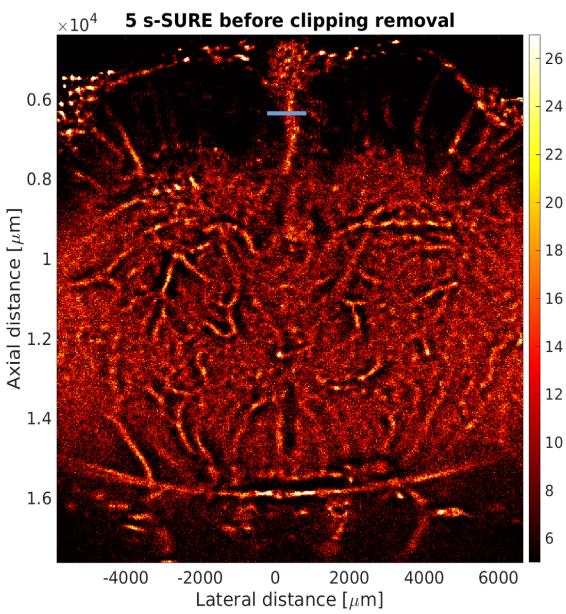
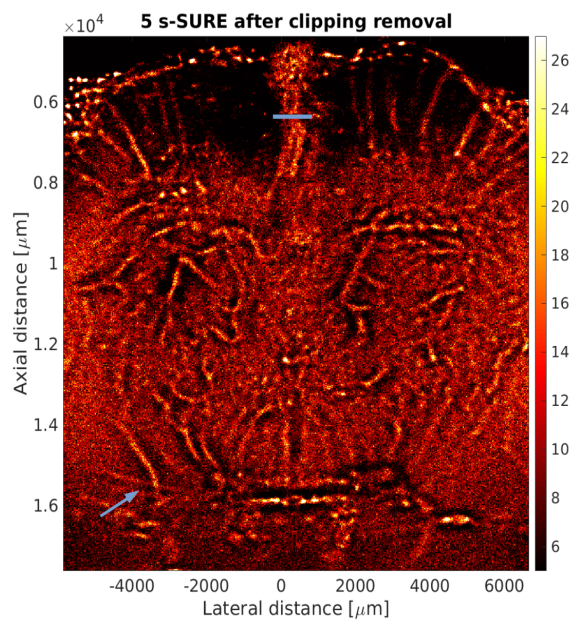


Figure 4: Clipped Power Doppler image. Outlined in blue is the clipping artifact that affects our region of interest.

The clipping removal algorithm was then applied to this data. Out of the 4036 received signals that constitute the image, 171 signals showed clipping (4.24% of signals). These signals were subsequently masked out. Figure 5b displays the 5-second SURE image obtained after applying the proposed clipping removal algorithm. The clipping artifact is nearly completely eliminated in the outlined area, with only a faint shadow remaining in the left area where the clipping once occurred (See blue arrow in Fig.5b).



(a) 5 seconds original SURE



(b) 5 seconds SURE after Clipping Removal

Figure 5: 5s SURE image before and after Clipping Removal with the same dynamic range. The blue arrow in (b) points at the light shadow that remains after applyin the clipping removal algorithm.

Comparing 5a and 5b, an enhancement of the effective dynamic range of the image is visible. In fact, the dynamic range has improved by almost 12% after applying the proposed algorithm. Because of this, vessels in the cortex of the rat brain that were previously undistinguisable are now visible.

Additionally, all the vessels that were visible in the original image are still visible in the image after the clipping was removed. Therefore, essential information of the image was not lost. However, in some parts of the image the vessels seem to be bigger after clipping removal. See for example, the profile of the main feeding vessel of the brain, indicated with a blue line in Fig. 5a and 5b. A profile comparison of that vessel in both images is shown in Fig. 6. When resolution worsens, images becomes less detailed, and as a result, features like blood vessels can appear larger or more blurred.

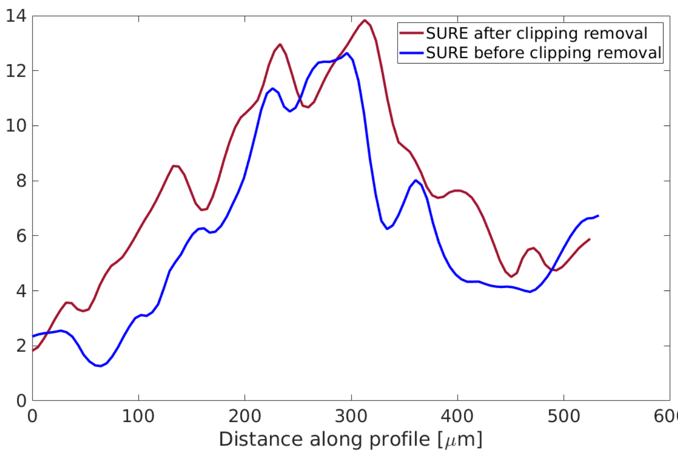


Figure 6: Vessel profile before and after clipping removal indicated with a blue line in Fig. 5. Smoothing was applied to the images, before creating the profiles to avoid sparsity due to short data duration.

4. DISCUSSION

The proposed method demonstrated an improvement in the dynamic range of the in-vivo rat brain image, while removing clipped signals in the data. Vessels in the cortex of the brain that were not visible in Fig. 5a, became visible after clipping removal (Fig. 5b), using the same dynamic range for visualization. However, as seen in the left part of Fig. 5b, a shadow of the clipping artifact remained. This is likely due to the direct masking of the clipped signals to zero, without a smooth transition between the non-clipped and clipped data. Smoothing techniques could be applied to the clipped areas to eliminate this shadow completely.

On the other hand, the phantom experiment demonstrated that the proposed method can be applied to many levels of clipping but is primarily effective in dealing with moderate levels of clipping. This is because masking out a large number of signals significantly affects image quality. In the current implementation of the clipping removal algorithm, if all received signals are affected by clipping, regardless of the percentage of the signal that is clipped, the method would discard all signals. In certain scans, such as those of the carotid artery, clipping may affect only a small percentage of the data, but if it impacts all channels, the loss of information in that region could be substantial. Therefore, further research is required to develop techniques for addressing clipping artifacts in severely affected images, as well as methods for localized clipping removal algorithms.

The proposed clipping removal algorithm was designed for SAUS. However, implementing the technique in systems like plane-wave ultrasound imaging should be relatively straightforward. In plane-wave imaging, multiple signals contribute to each pixel, similar to in synthetic aperture imaging. Therefore, the method described in this paper could be adapted for use in plane-wave systems with minimal modifications.

On another note, while clipping removal can improve dynamic range and eliminate clipping artifacts from the image, it comes at the cost of reduced resolution. Therefore, researchers must consider whether they prioritize maintaining fine resolution or removing clipping artifacts and enhancing the dynamic range of the image.

5. CONCLUSION

This paper presented a post-processing method for removing clipping artifacts in SAUS, that can easily be applied to plane wave imaging. The method effectively masks out clipped signals while preserving non-clipped contributions.

Single-wire phantom results demonstrated that the method can be applied to remove mild levels of clipping without a significant loss in contrast and resolution. In fact, when up to 30 % of the data was clipped, the loss in resolution after applying clipping removal was lower than 2.5% and the contrast decreased less than 7.9%, when compared with the original non-clipped image.

On the other hand, when the proposed algorithm was tested in vivo, it significantly reduced clipping artifacts and improved the visibility of some features such as blood vessels by expanding the effective dynamic range. Furthermore, due to its simplicity it can easily be implemented in clinical synthetic aperture imaging systems, to potentially improve diagnostic accuracy.

6. ACKNOWLEDGMENTS

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