# Real-Time Implementation of a Dual-Mode Ultrasound Array System for Image-guided Interventions

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# Disclosures

Dr. Ebbini is a consultant for International Cardio Corporation, the company sponsoring this research. Additionally, Dr. Ebbini is entitled to receive royalties under a licensing agreement between International Cardio Corporation and the University of Minnesota. This relationship has been reviewed and managed by the University of Minnesota in accordance with its conflict of interest policies.

The University of Minnesota has filed two patent applications and one provisional application based on technology described in this presentation

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# Overview

- Dual-Mode Ultrasound Arrays
- Hardware-Software Support
- In-Vivo Targets
  - Rat Hind Limb
  - Swine Femoral Artery
  - Rabbit Carotid and Iliac Arteries
- Real-time Monitoring and Control

# Dual-Mode Ultrasound Arrays

- Same Elements for Therapy and Imaging
  - Inherent Registration for Guidance
  - Focal spot Interrogation for Monitoring
  - Image the Whole Beam for Obstructions
- Imaging Quality Consistent with Characteristics of PSF
- Does not compromise therapeutic output when used in conjunction with pFUS

# More Information


- Real-time Implementation of a Dual-Mode Ultrasound Array System: *In Vivo Results*. Casper A, Liu D, Ballard J, Ebbini E. IEEE T-BME 2013 May 21. PMID: 23708766.
- Adaptive transthoracic refocusing of dual-mode ultrasound arrays. Ballard JR, Casper AJ, Wan Y, Ebbini ES. IEEE Trans Biomed Eng. 2010 Jan;57(1):93-102. PMID: 19651547.
- Imaging with concave large-aperture therapeutic ultrasound arrays using conventional synthetic-aperture beamforming. Wan Y, Ebbini ES. IEEE T- UFFC. 2008 Aug;55(8):1705-18. PMID: 18986915
- Dual-mode ultrasound phased arrays for image-guided surgery. Ebbini ES, Yao H, Shrestha A. Ultrason Imaging. 2006 Apr;28(2):65-82. PMID: 17094688

# DMUA Examples: Piezocomposite (Imasonic, France)

- 1-MHz, 64 Element Array
- 100mm ROC
- 1.5x50 mm Elements
- 2 mm Pitch (1.33 λ)
- 40% Fractional Bandwidth

**Ebbini et al, Ultrasonic Imaging, 2006**

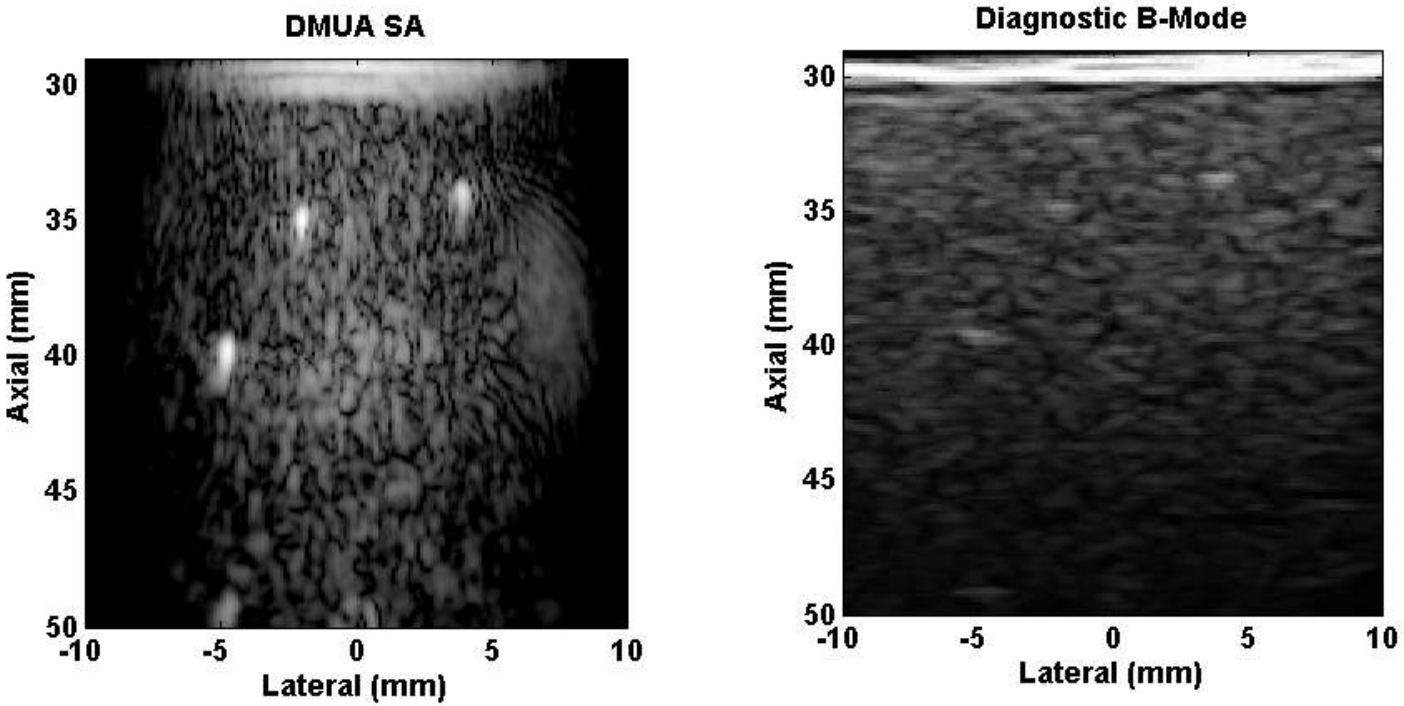
- 3.5-MHz, 2x32 Element Array
- 40mm ROC
- 1.2x6.8 mm Elements
- 1.5 mm Pitch (3.75 λ)
- 55% Fractional Bandwidth

**Casper et al, IEEE T0BME, 2013**

# DMUA Imaging

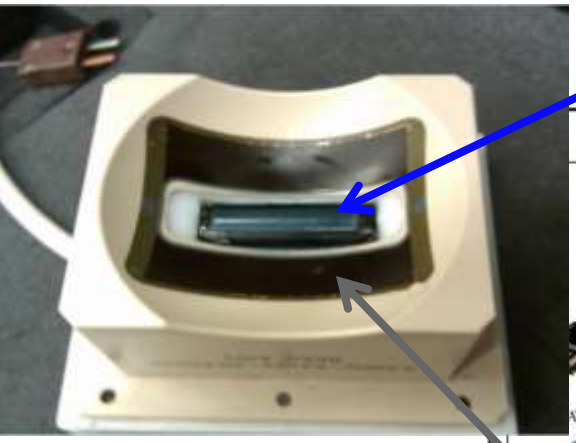
- Synthetic Aperture
  - Field of view
  - Highest Quality Conventional BF Image
- Single Transmit Focus
  - Imaging Using Therapeutic Beam at Sub-therapeutic levels
  - Allows for Direct Visualization of Beam Path
    - Focus
    - Obstructions

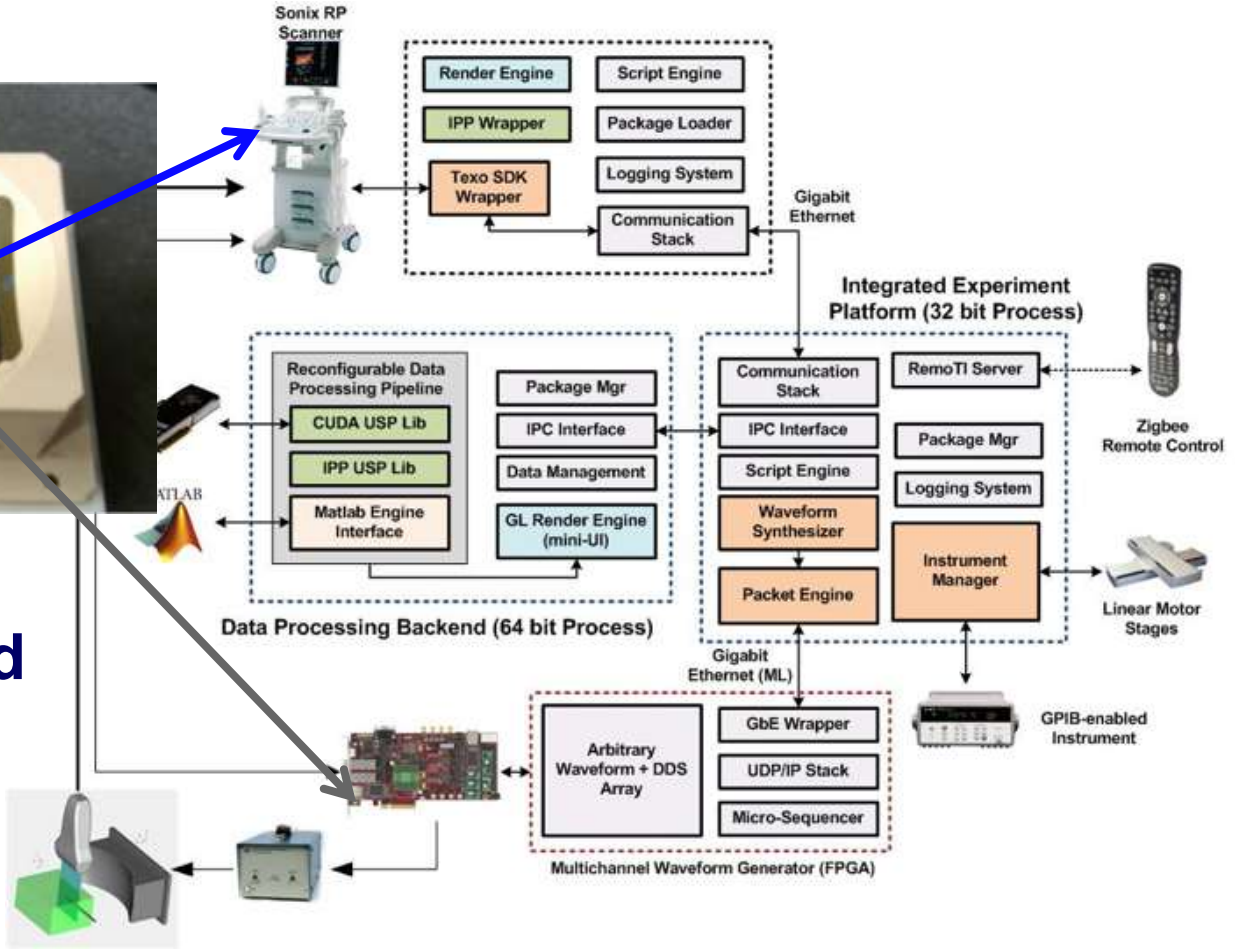
# DMUA vs Linear Array Probe (CIRS Phantom)




- 3.5-MHz DMUA, Geometric Focus 40 mm
- Excellent Lateral Resolution
- Elongated Axial Resolution

# DMUA System: Software-hardware Support

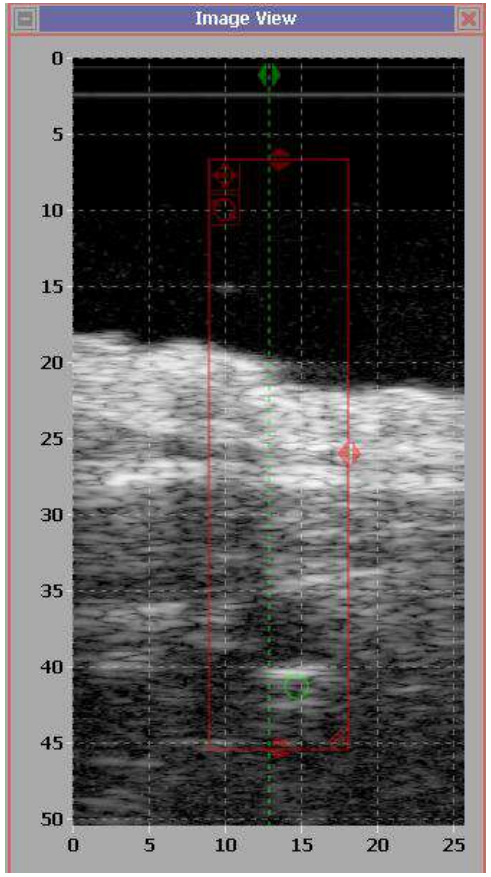


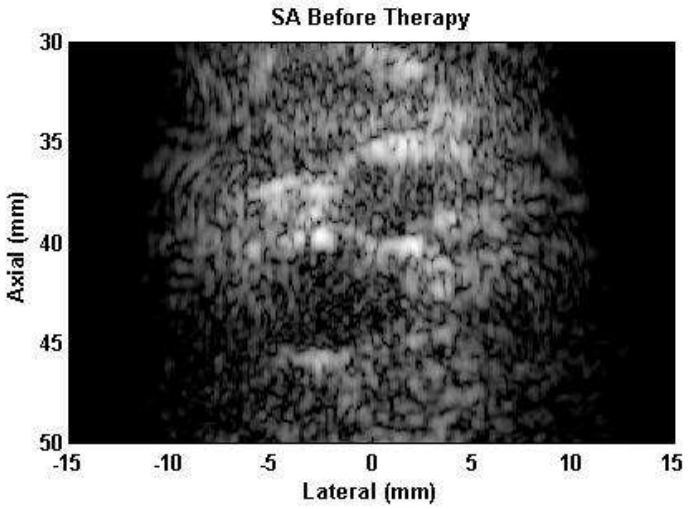


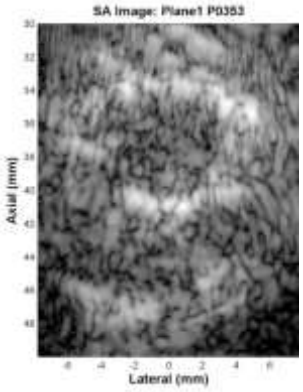

**Real-time Synchronized M2D and DMUA Imaging**

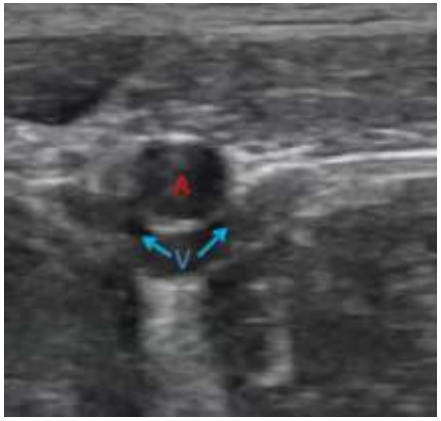
**M2D: Liu and Ebbini, IEEE T-BME, Jan'10.**

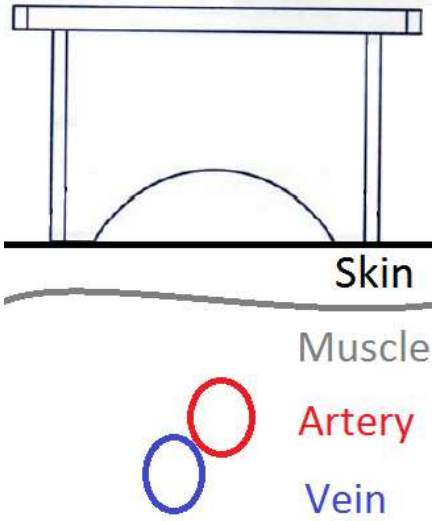
# Femoral Artery and Vein in FH Swine: SA Imaging and Comparisons



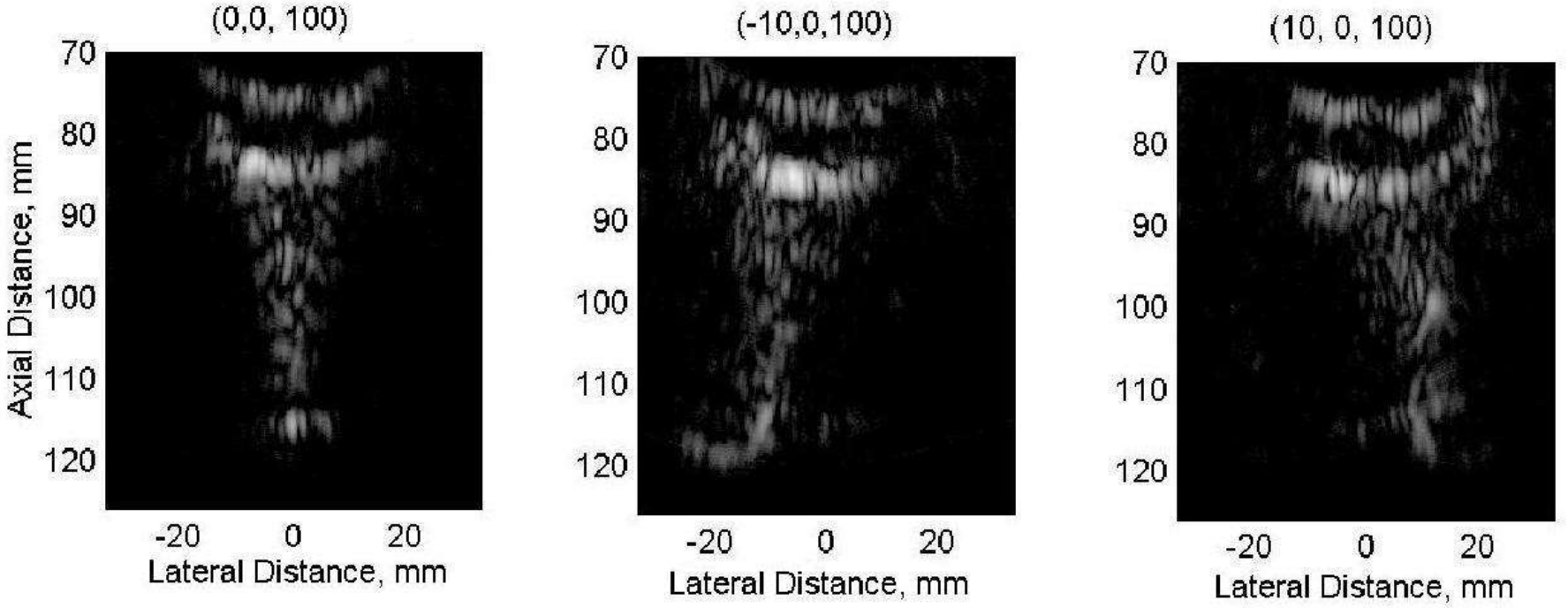



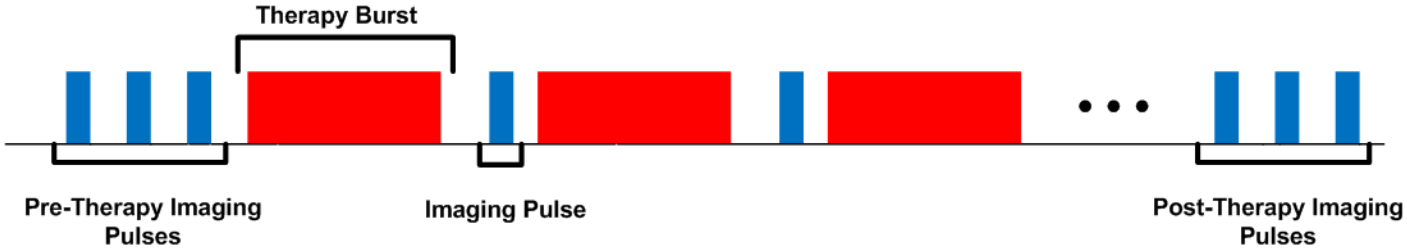



# DMUA Single Transmit Focus Imaging



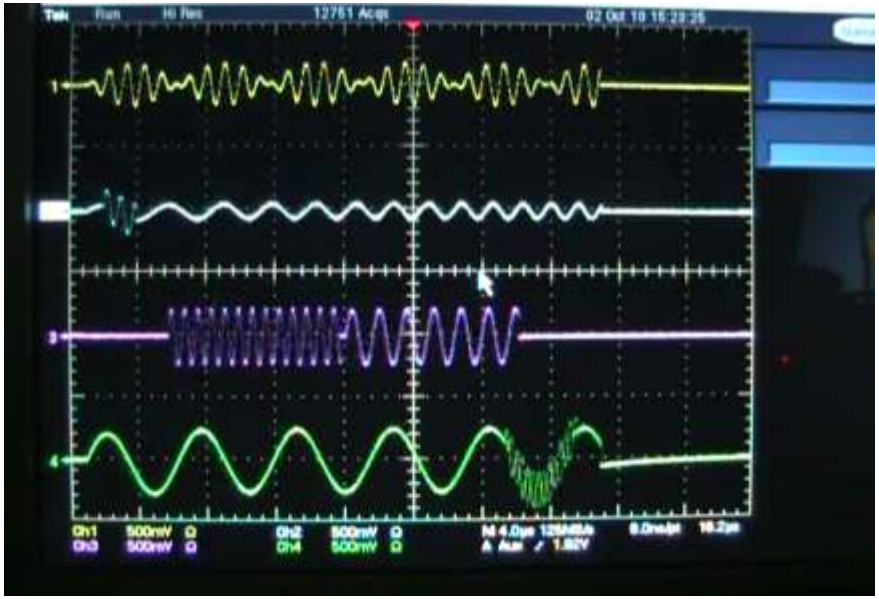

- 1-MHz DMUA, Geometric Focus 100 mm
  - Speckle Generating Phantom
- Direct Visualization of the Beam (Throughout the treatment region)

# Real-Time DMUA System: Imaging-therapy Sequence




- Fast Interleaving HIFU with Imaging
  - High Power Transmitter with CW and P/E Capabilities
  - Multi-Channel Receive System
- Software Defined Ultrasound
  - Reconfigurable Transmissions
  - Reconfigurable Signal Processing and Beamforming Pipeline

# Array Excitation



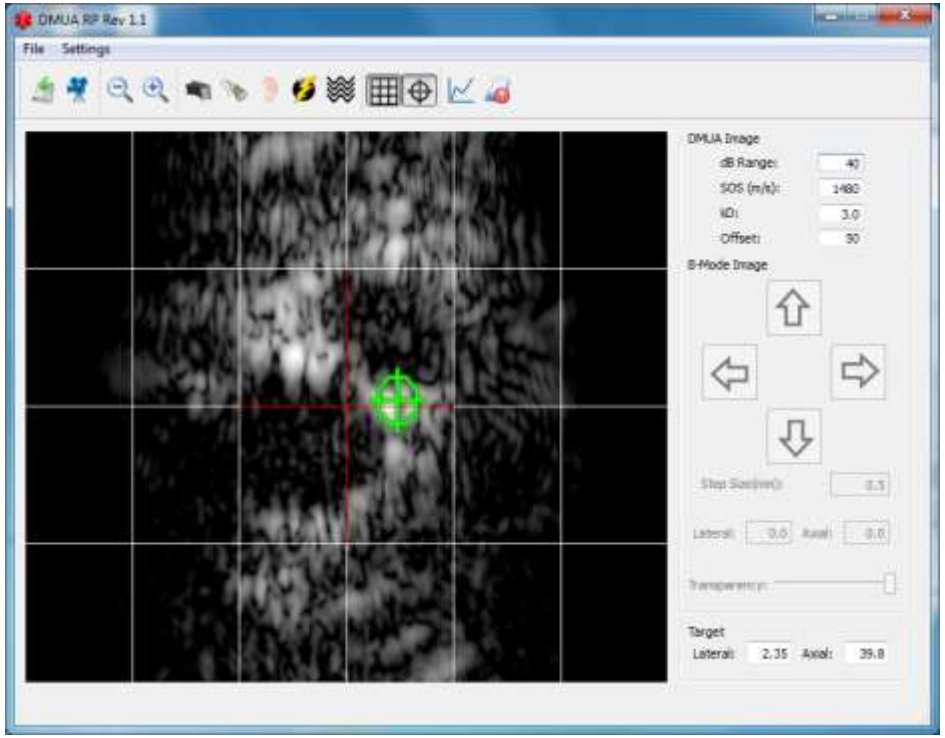
- 32-Channel Arbitrary Waveform Generator
- 10-Watt Linear Amplifier
- Reconfigurable Matching Network
- Adaptive Optimal Real-time Refocusing at 1000 fps

# Data Acquisition


- Independent Signal Path on each Element
  - 60 MSPS, 12-Bit ADC
  - 1 Virtex 5 SX50T per 16 Channels
  - Gigabit Ethernet Connection to Computer
- Up to 2K FPS

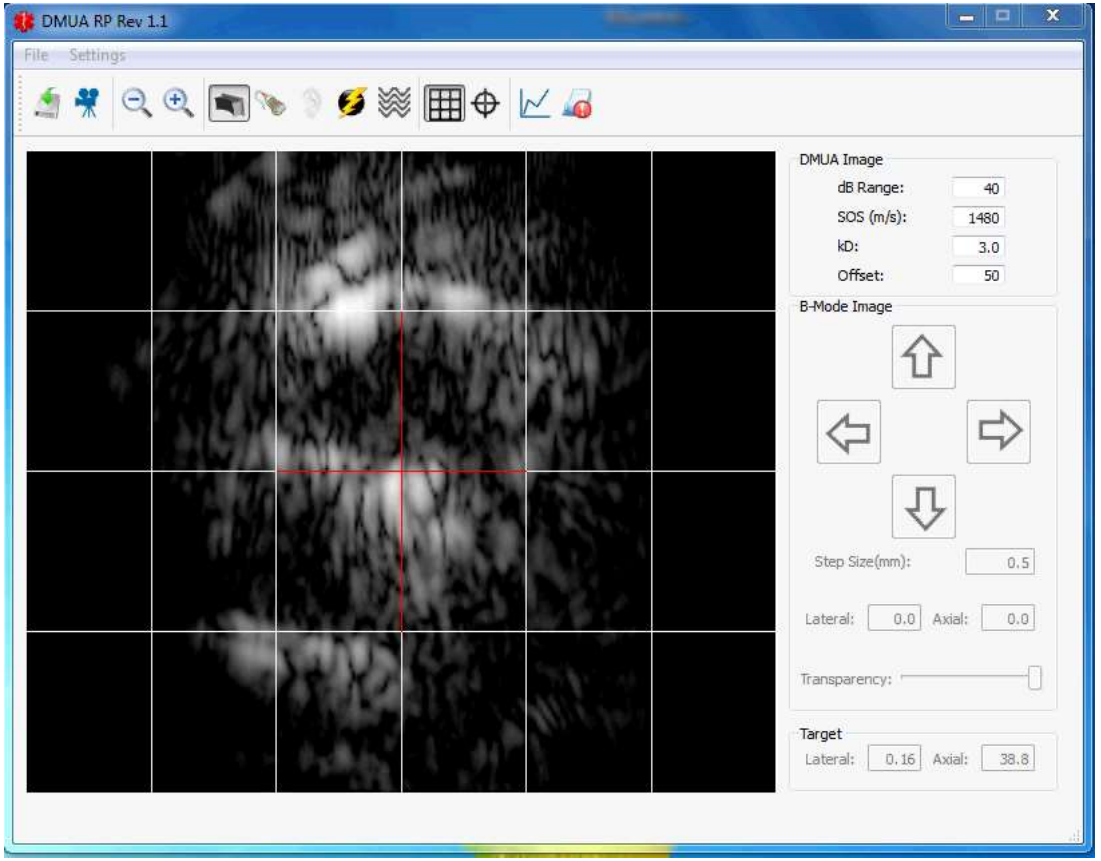
# Processing and Display

- RF Data Transferred to Computer
- Graphical Processing Unit Beamforms Data
  - GTX 285
  - 33 FPS SA
- GUI for Guidance and Targeting



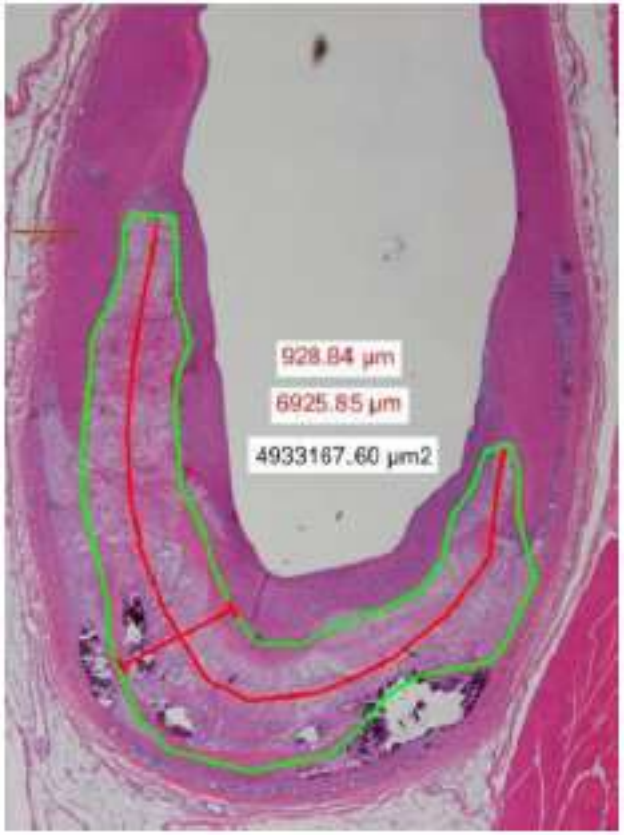
# In Vivo Imaging and Targeting

- 5 mm Grid Spacing
- Geometric Focus Intersection of Red Lines
- Green Target Represents Ablation Location (No HIFU Delivered)

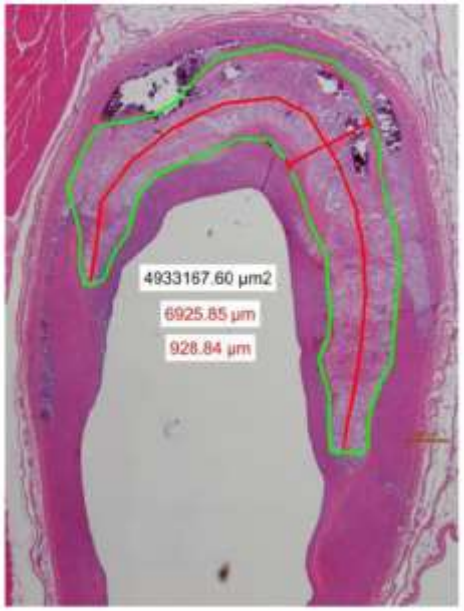


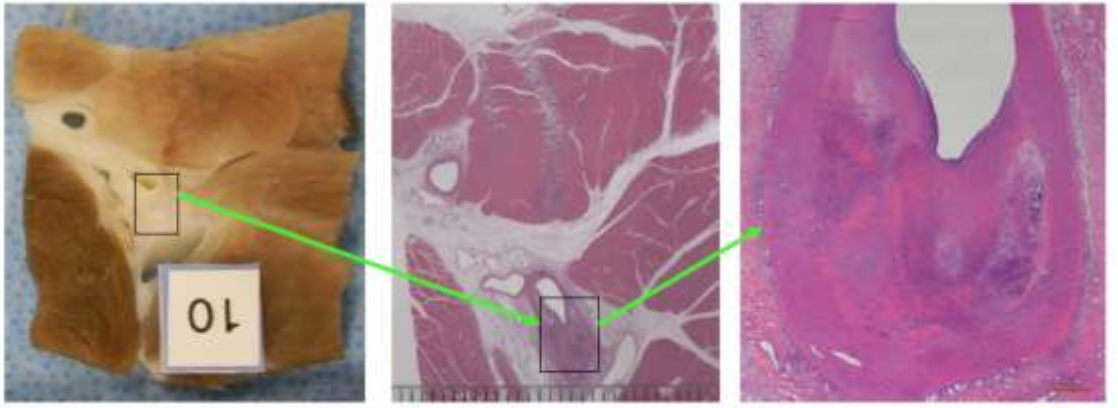
# Swine Femoral Artery: Damage

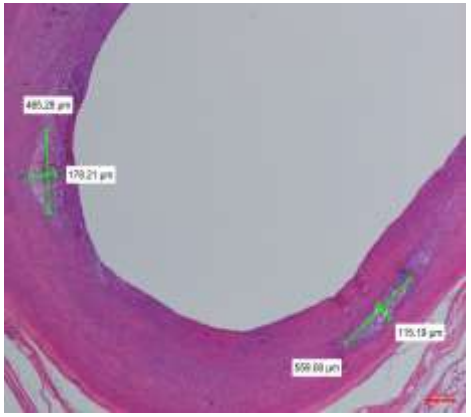
- 7 Shots spaced 1 mm apart on vessel wall
- Typical Thermal Necrosis within the plaque
- No Damage to the Endothelium
  - Heat Sink Effect

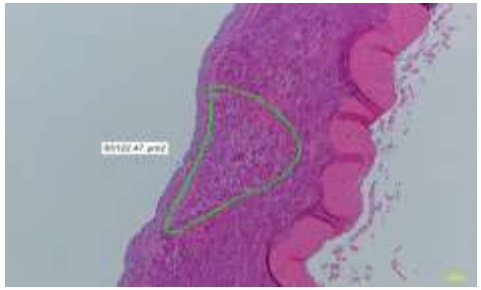


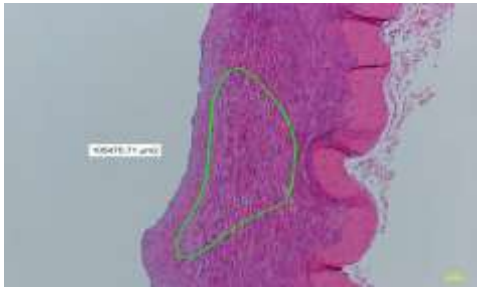
# Ground Truth Data Provided by Histology



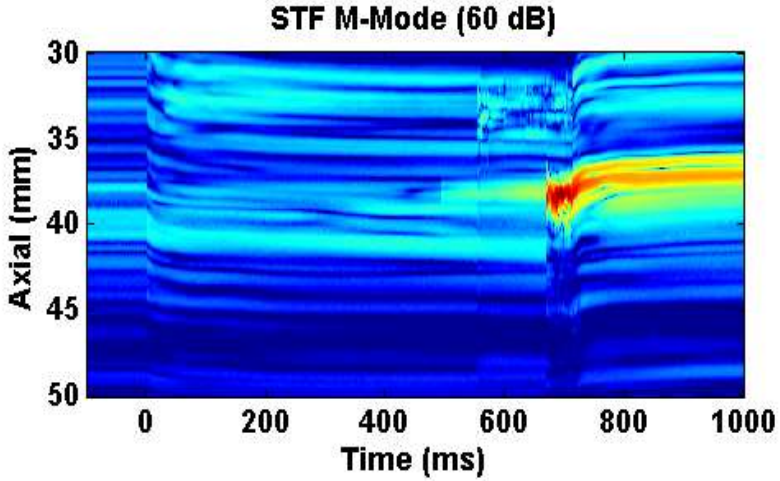


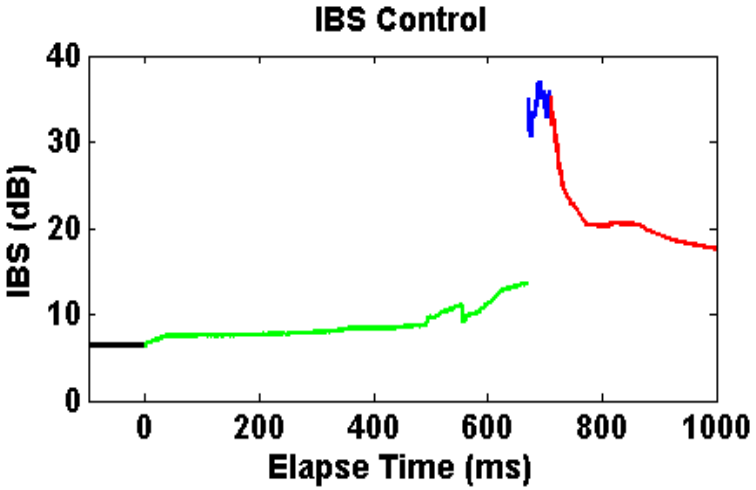


# Continued Ablation

- Immediate cessation may limit damage
- Modified Protocol
  - Detect Change
  - Continue for a preset duration

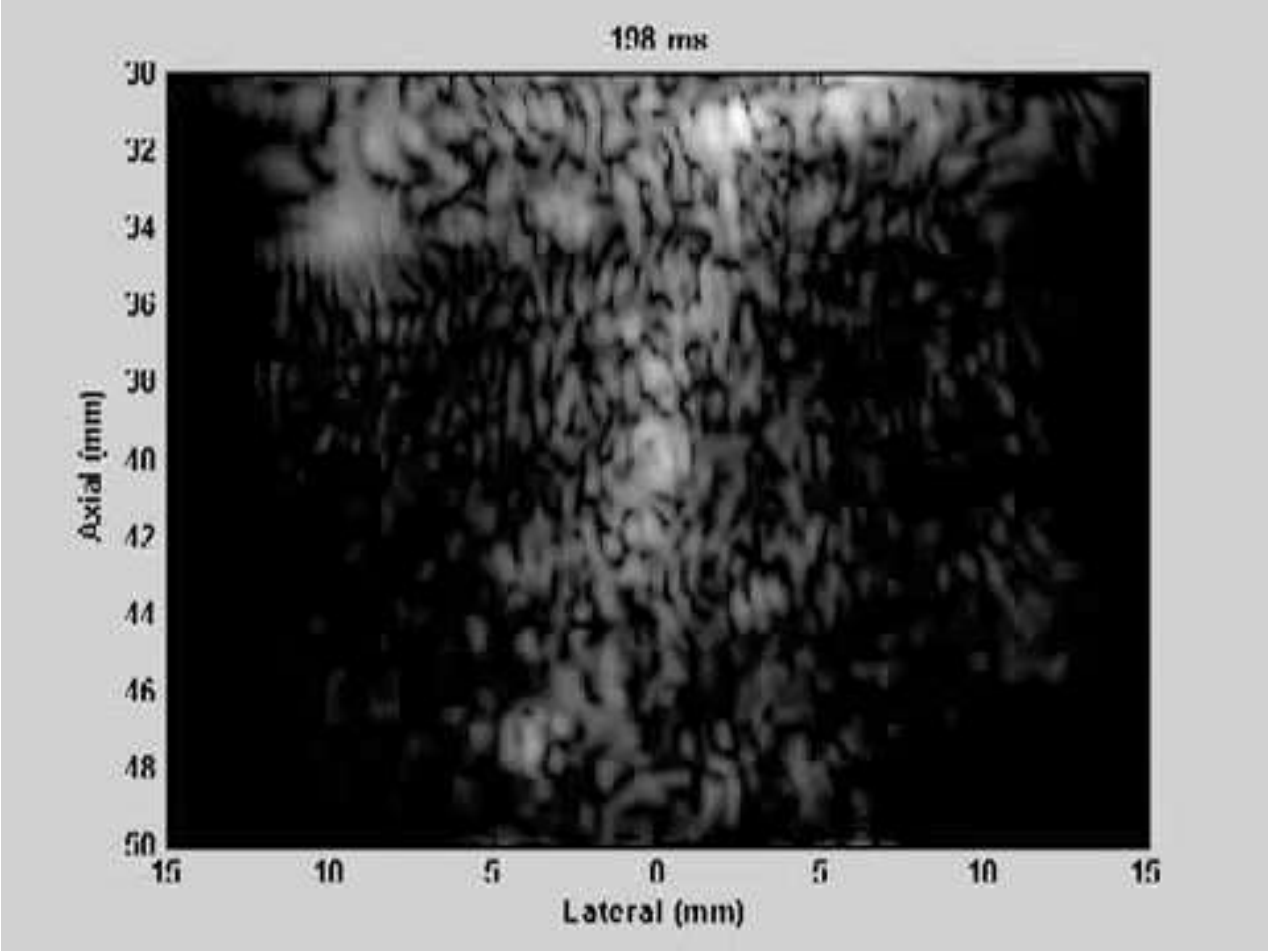
# Continued Ablation




- Therapy continued 40 ms after detection (blue)

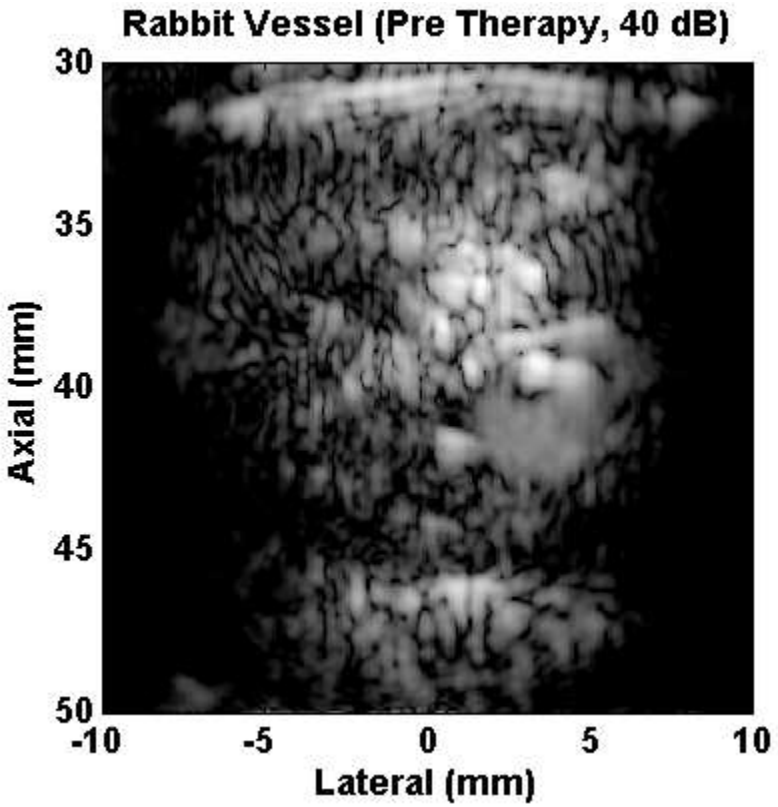
# STF Movie


198 ms
30
32
34
36
38
40
42
44
46
48
50
Axial (mm)
15
10
5
0
5
10
15
Lateral (mm)

# New Zealand Rabbit

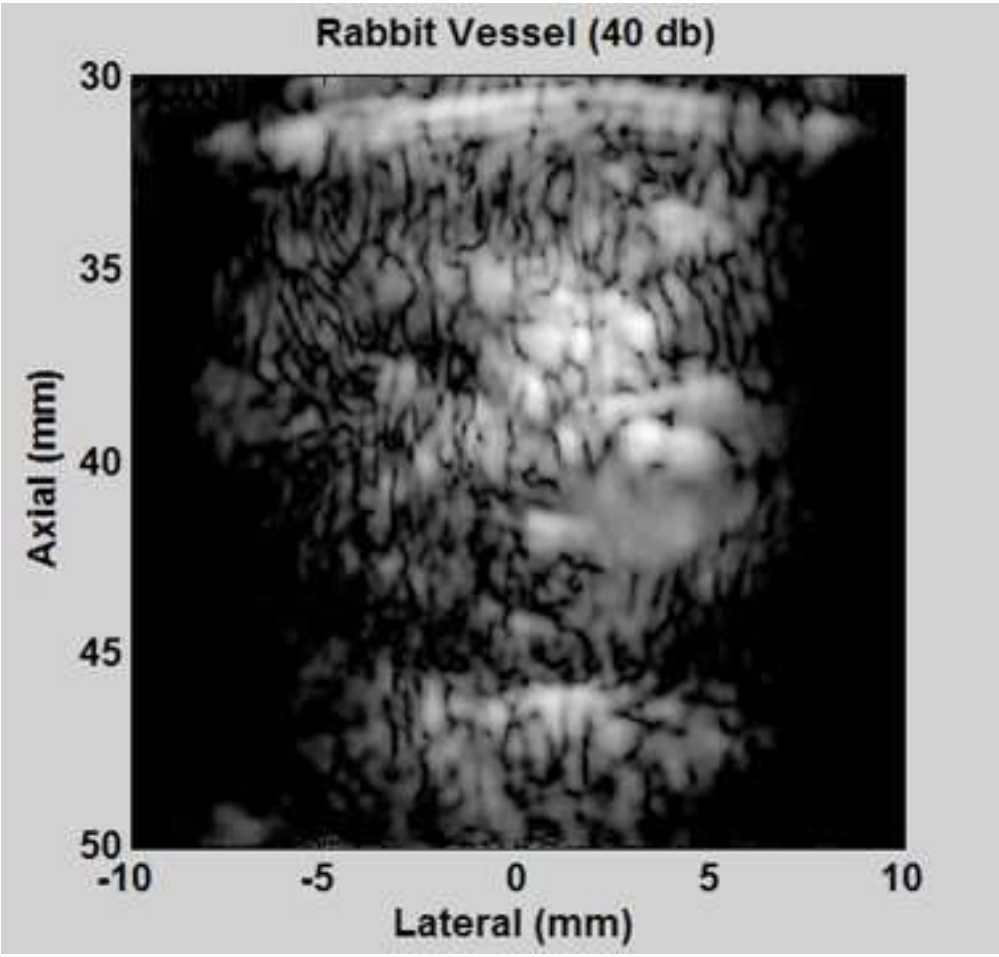
- In Vivo experiments in ~3 kg Rabbit
- Targeted carotid artery
- Deliver therapy until an echogenic change is detected
  - Continue additional 200 ms

# Pretreatment Image

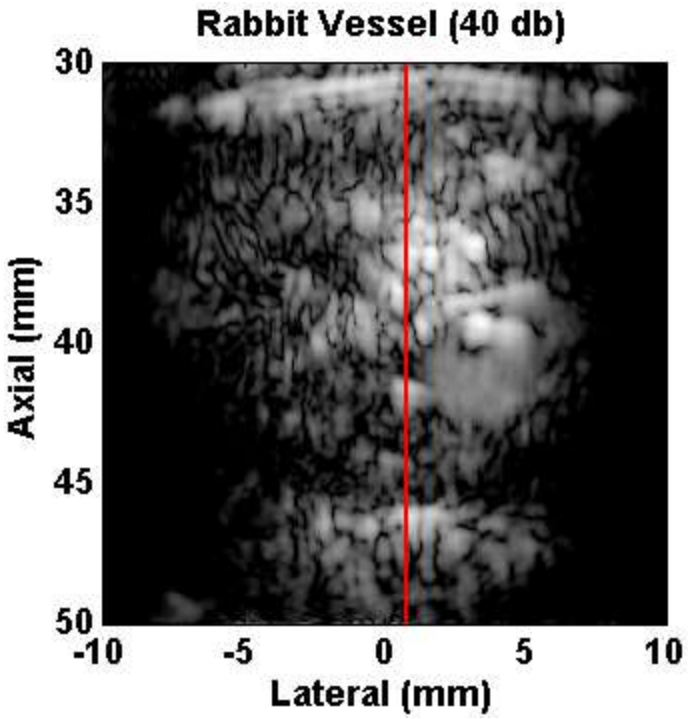


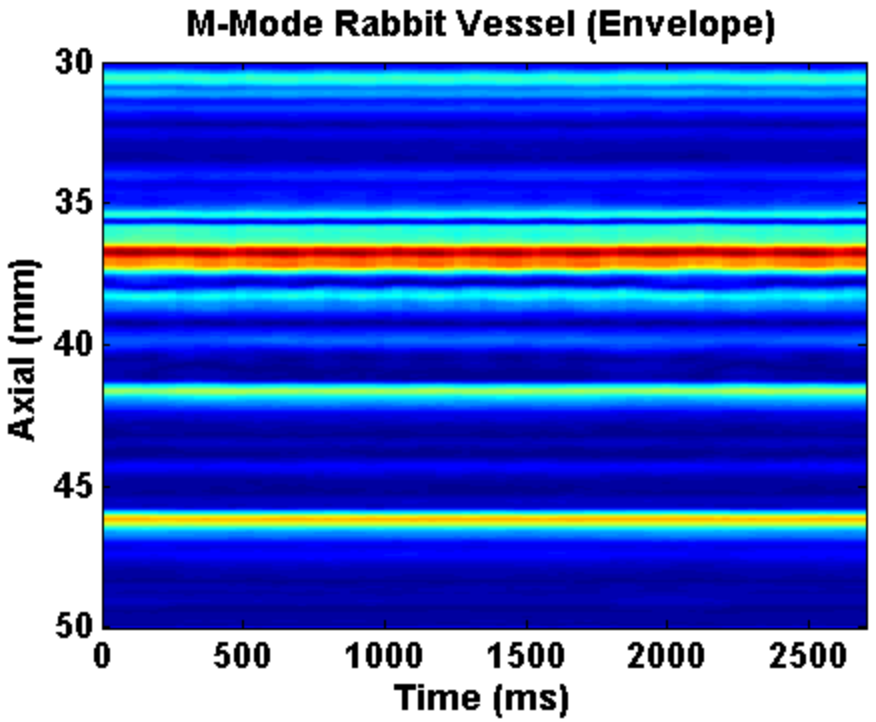

- Tissue surface ~ 31 mm
- Vessel slightly proximal to focus
- Static image

# Real-time SA Imaging (30 fps)

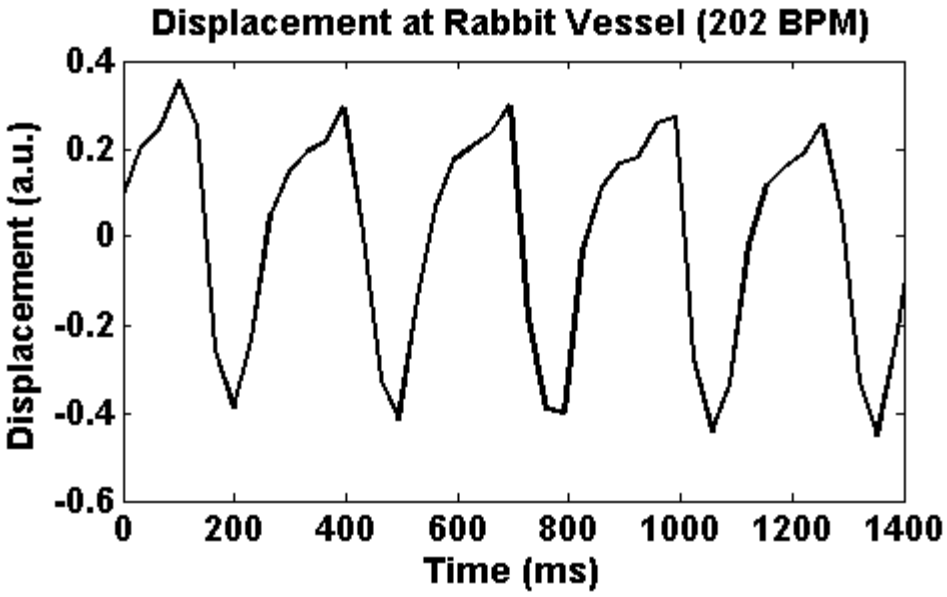


# Visualization of Dynamics



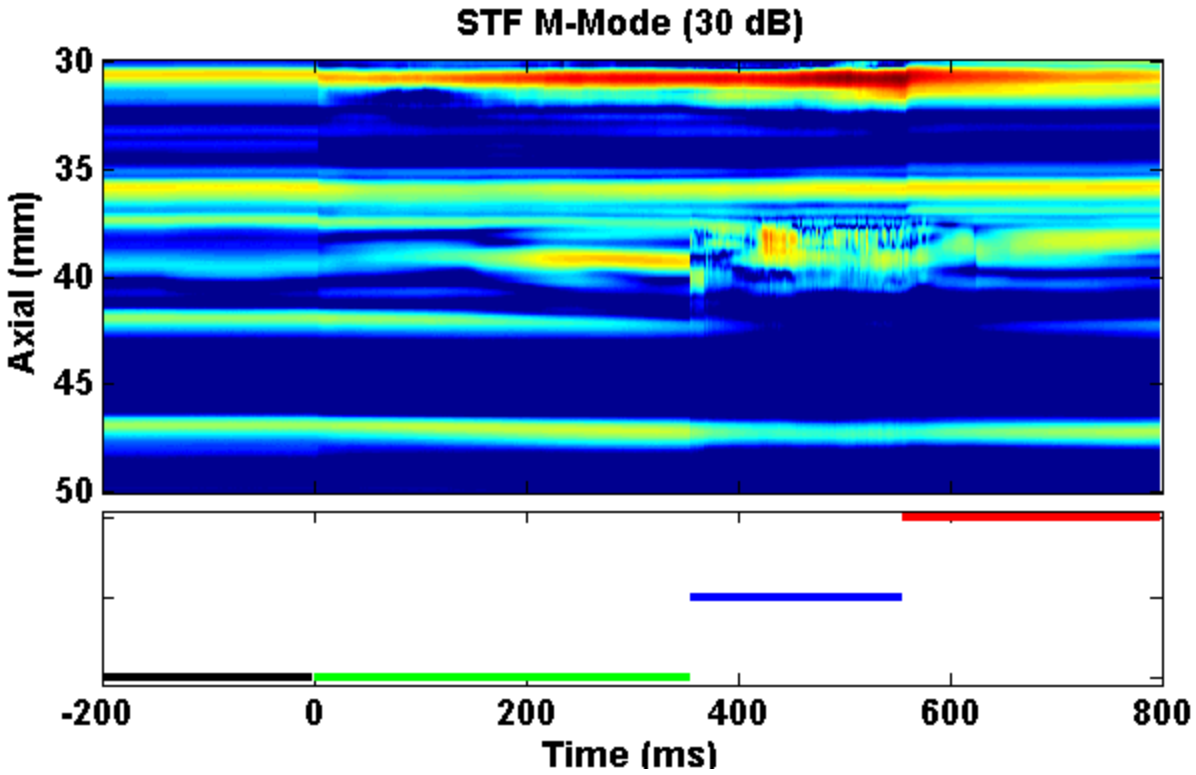



# Displacement tracking



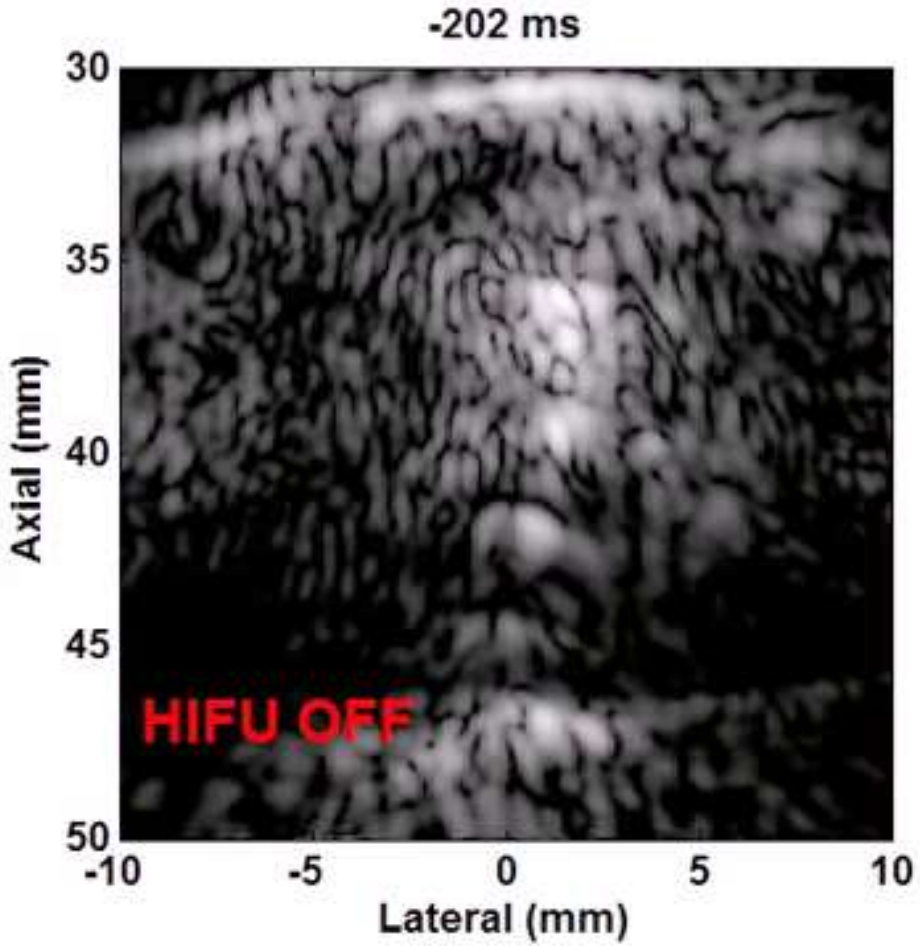

- Phase based measurements
- Track very small displacements
- Vessel Wall
  - Recorded heart rate of 208 BPM

# Controlled Ablation




- Therapy continued 200 ms after detection (blue)

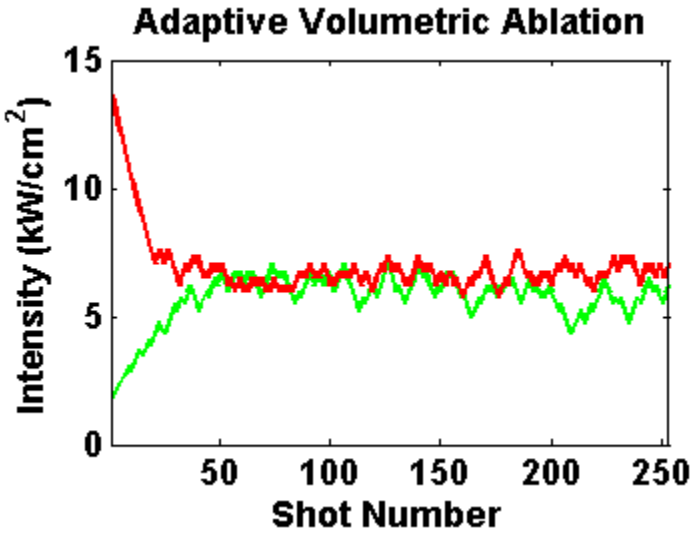
# Ablation Dynamics

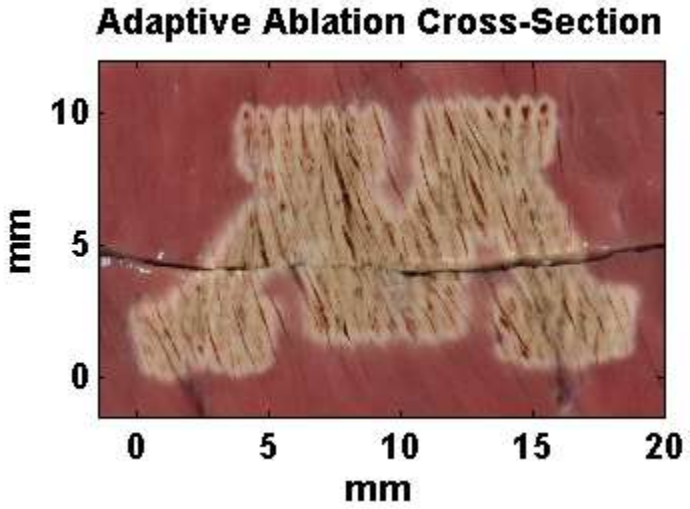


# Conclusions

- Demonstrated a Real-Time Ultrasound-Guided Focused Ultrasound System
  - Dual-Mode Array Used to Image and Guide Therapy
  - Visualized and Targeted Vascular Structures
  - Real-time control of lesion formation *in vivo*

# Next: Adaptive Control of Lesion Formation




- System converges to appropriate power level based on *in situ* conditions
- Independent of starting point

# Comparison with Open-loop Control

- Ablation with (right) and without control (left)
- Bubble Activity Detector (top)
- Cross Section view of tissue (bottom)