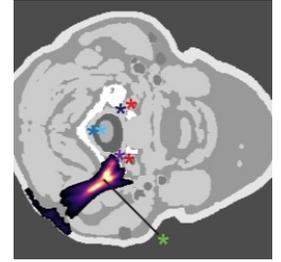Aug 07, 2025

🌐 Simulation of MR-Guided Focused Ultrasound for Cervical Facet Joint Ablation Using MRI and CT-Based Anatomical Models

DOI

dx.doi.org/10.17504/protocols.io.5jyl8wxk6l2w/v1

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Protocol status: Working
We use this protocol and it's working

Created: April 28, 2025

Last Modified: August 07, 2025

Protocol Integer ID: 189852

Keywords: cervical spine, MRI, CT, simulation, FUS, MRgFUS, focused ultrasound, facet joint, guided focused ultrasound for cervical facet joint ablation, guided focused ultrasound, cervical facet joint ablation, focused ultrasound, focused ultrasound transducer type, cervical facet joint, treatments to cervical facet joint, ultrasound transducer type, simulation of mr, using mri, multiple cervical level, simulating mr, based anatomical model, imaging acquisition, resolution mri, tissue response, anatomical models this protocol

Abstract

This protocol outlines the methods for simulating MR-guided focused ultrasound (MRgFUS) treatments to cervical facet joints using high-resolution MRI and CT data. It includes imaging acquisition, segmentation, acoustic and thermal simulation, and safety analysis using two focused ultrasound transducer types. Tissue response to focused ultrasound was modeled and evaluated across multiple cervical levels and beam angles to assess feasibility and safety.

Materials

Equipment	Specifications
MRI Scanner	3T (MAGNETOM Skyra/Vida) or 1.5T (MAGNETOM Aera), Siemens
CT Scanner	Clinical CT system with cervical spine protocol
Segmentation Software	Seg3D
Simulation Tools	HAS algorithm and finite difference solver for Pennes bioheat equation
Tissue Property Database	IT'IS Foundation Tissue Properties (acoustic and thermal)

Troubleshooting

Before start

Ensure IRB approval for retrospective use of clinical imaging data.

Participant Selection and Imaging

1 We simulated ultrasound treatments in the necks of six individuals. Participants included four patients referred for general neck imaging and two healthy volunteers. Imaging was performed on either a 3T (MAGNETOM Skyra or Vida) or 1.5T (MAGNETOM Aera) Siemens scanner.

1.1 3T Imaging Parameters:
- Gradient echo
- TR = 6.68 ms
- TE = 2.46 ms (in phase), 3.69 ms (out of phase)
- Echo train length = 2
- 1 average

1.2 1.5T Imaging Parameters:
- Gradient echo
- TR = 6.97 ms
- TE = 2.39 ms (in phase), 4.47 ms (out of phase)
- Echo train length = 2
- 4 averages

1.3 Axial T1 Dixon sequences were used for visualizing fat and muscle. Zero-filling was applied to achieve 0.5 mm isotropic resolution. All imaging was IRB-approved.

CT-Based Anatomical Measurement

2 We analyzed cervical spine CTs from 40 individuals for planning transducer reach.

2.1 Measurements included:
- Depth from skin to each facet joint target (0-degree angle)
- Distance between left and right targets

Treatment Strategy and Scope

3 We simulated treatment at all cervical levels bilaterally, assuming mechanical transducer motion between angles of 0–30° in the axial plane. Simulations investigated safety of targeting facet joints at 0°, 15°, and 30° using FUS.

Target and Off-Target Locations

4   Facet joints from C2-3 to C6-7 were manually identified by a neuroradiologist on MR images. Off-target structures included spinal nerves, the spinal cord, and major arteries (vertebral, carotid).

Segmentation Methods

5   Seg3D was used to segment MRI into 8 tissue types: water, CSF, vessels, fat, muscle, skin, bone, spinal cord.
- Non-skin layers: thresholding → manual correction → isolation (Boolean Remove)
- Skin layer: smoothed dilation/erosion on all-tissue mask + Boolean Remove

Ultrasound Simulations

6   We used the Hybrid-Angular Spectrum (HAS) method to simulate ultrasound propagation. Transducers were modeled using the Rayleigh-Sommerfeld integral. Tissue acoustic properties were from the IT'IS Foundation database.

Each model underwent 60 simulations (5 cervical levels, 2 sides, 3 angles, 2 transducers). Output was 3D pressure and power deposition. Nonlinear effects were ignored (P < 5 MPa).

Thermal Simulations

7   Thermal effects were modeled using the Pennes bioheat equation with 100 W ultrasound power. Assumptions:
- Boundary temperature = 37°C
- Tissue perfusion effects modeled for blood vessels

$$\rho c_p \frac{\partial T}{\partial t} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - w c_p (T - T_{ar}) + Q$$

Pennes bioheat equation

Thermaldose (CEM 43°C) calculated over 20 s sonication and 60 s cooling using:

$$\text{CEM at } 43°C = \cdot \int_0^t R^{T-43} dt$$

(R= 2 if T≥43°C; R = 4 if T<43°C)

7.1 Code for simulations: **GitHub**

Tissue Ablation and Safety

8 Ablation target: 60°C or >240 CEM.

Transducers

9 Transducer S11: 256-element, symmetric, 1 MHz, 11 cm focal length
Transducer A10: 256-element, asymmetric, 1 MHz, 10 cm focal length

Transducer Comparison

10 Free-field tests showed S11 produced 120.7% higher peak pressure (4.7 MPa) vs A10 (3.9 MPa). Simulations recorded:
- Peak temp at target
- Mean temp in 10 mm ROI
- Temp at off-target sites

Statistical tests:
- Normality: Anderson-Darling
- Significance: Wilcoxon signed-rank (only ΔT > 5°C tested)

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