Interstitial Ultrasound Ablation of Paraspinal and Vertebral Tumors: Patient-Specific Simulations & Treatment Planning

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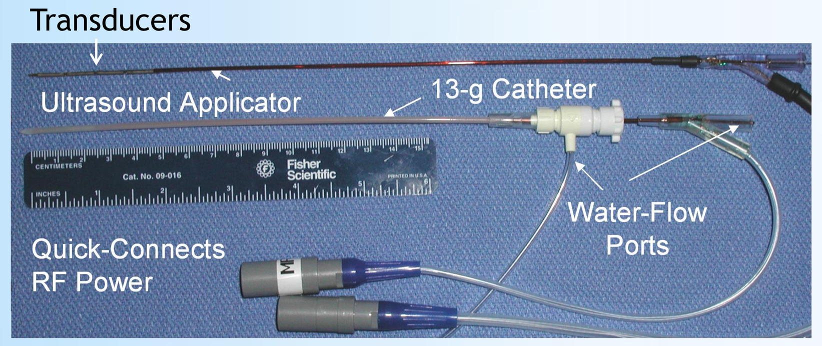
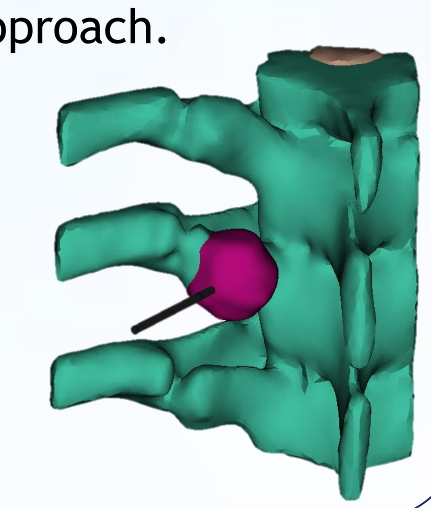
Introduction

Interstitial ultrasound is a novel tool for 3D control of thermal ablation, with potential advantages for thermal ablation of tumors near the spine and highly osteolytic tumors within the vertebrae. Preferential ultrasound absorption at the bone/tumor boundary would help ensure that the entire tumor is heated to lethal temperatures. The ultrasound applicator can be inserted directly into the tumor, and power distributions controlled along the length and circumference of the applicator. As there are several highly sensitive structures near the spine, such as the spinal cord, nerves, blood vessels, lungs, etc., great care must be taken during treatment planning. The applicator's placement, the applicator type, and the applied power distribution must be carefully tailored to each patient's anatomy so the tumor is fully ablated without damaging any sensitive structures nearby. The objective of this study is to develop a 3D patient specific biothermal model and treatment planning platform to investigate the feasibility of this approach.

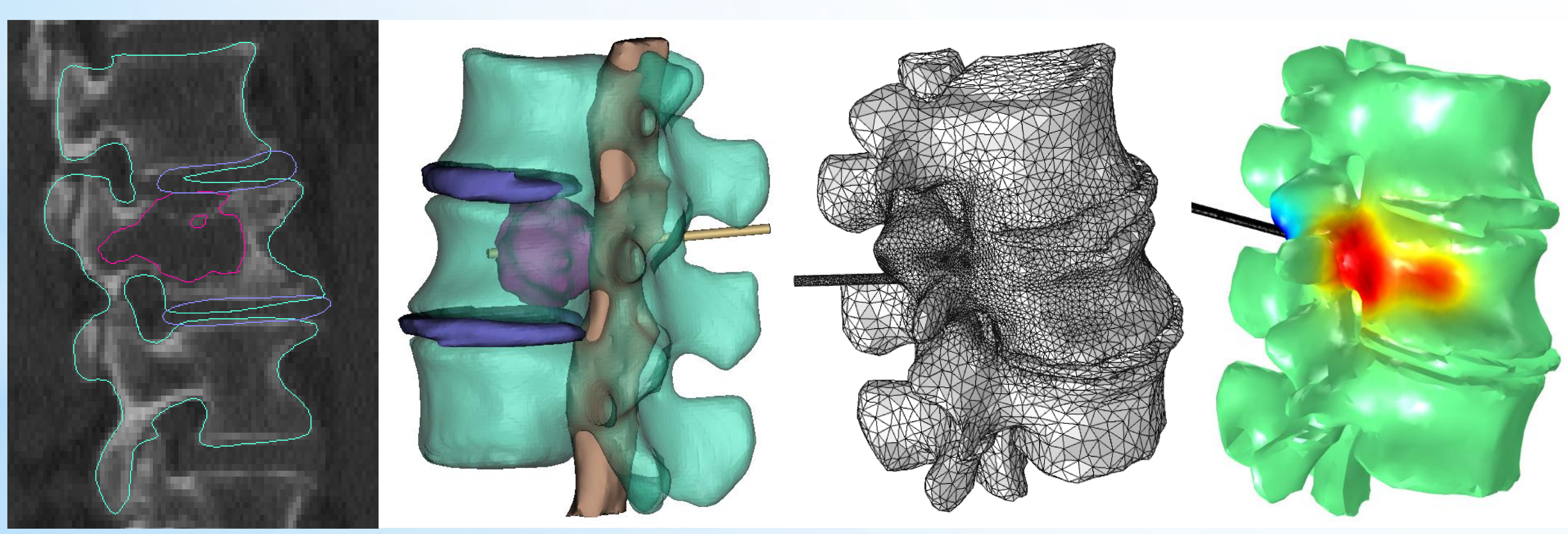


Left: Interstitial applicators. There is a row of cylindrical transducers near the left tip that emit ultrasound radially outwards, each with separate power control. The lower applicator is shown within a water-cooled implant catheter that is inserted directly into or adjacent to the tumor. Right: Tumor (magenta) invading vertebrae (green) with applicator (black) inserted.



Methods

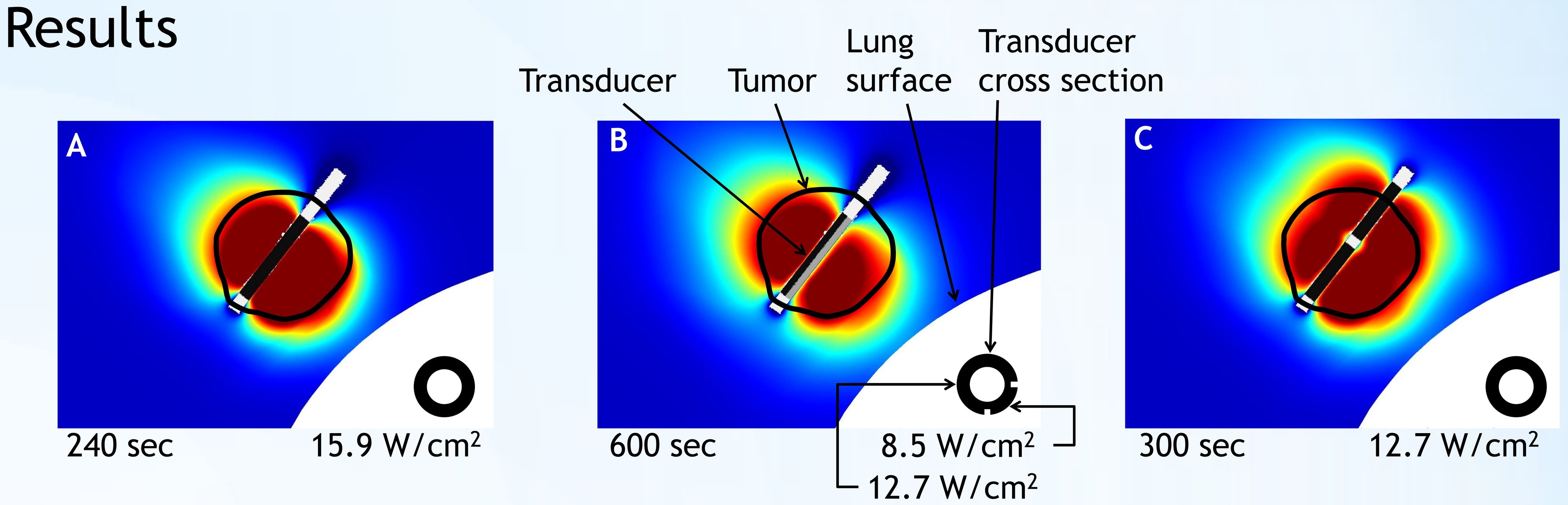
The Mimics Innovation Suite was used to develop 3D biothermal and acoustic finite element models of paraspinal and vertebral tumor ablation in 3 patient anatomies. 3D models were created based on CT scans segmented in Mimics (Materialise). A cylindrical interstitial applicator was added to the geometry and a finite element mesh created in 3-matic (Materialise). The meshes were imported into Comsol Multiphysics where ultrasound power deposition, transient heat transfer, and temperature distributions during interstitial ultrasound ablation were simulated. Heat transfer was modeled using the Pennes bioheat transfer equation. The tissue was considered ablated when it reached 52°C, and spared if kept below 45°C. The 3D geometries and simulation results were used to select the optimal treatment parameters for each patient case.

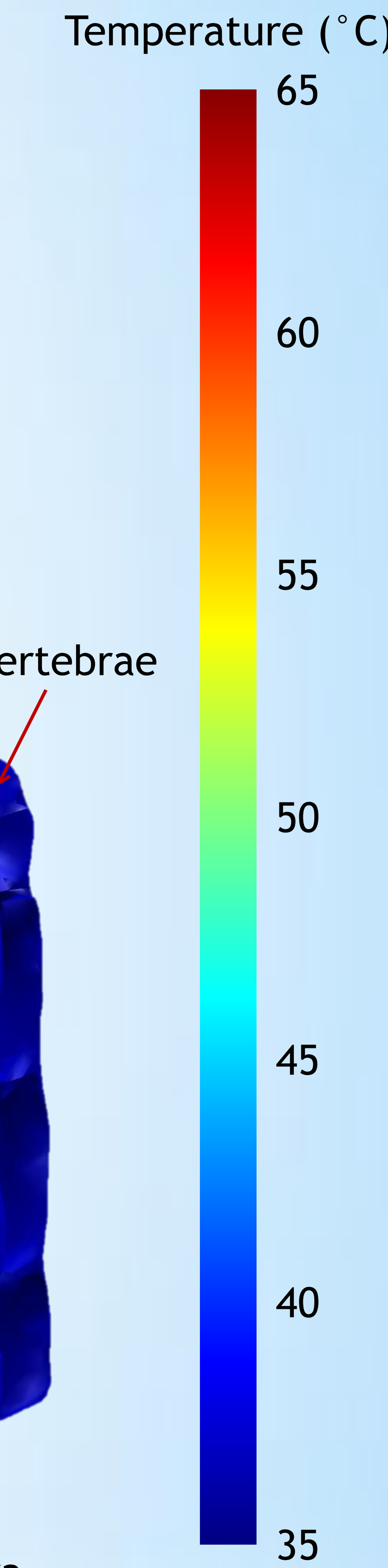


Segmentation → Applicator placement → FE mesh → Temperature map

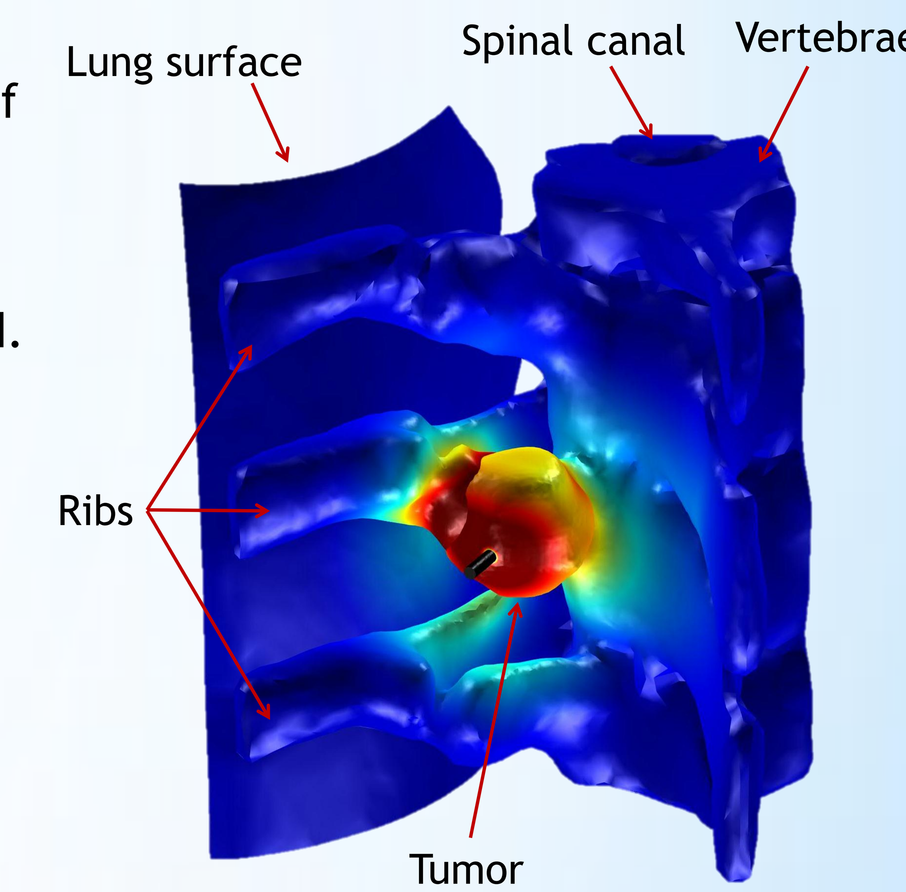
Adjust applicator placement, number of transducers, transducer length, aiming, and power as necessary

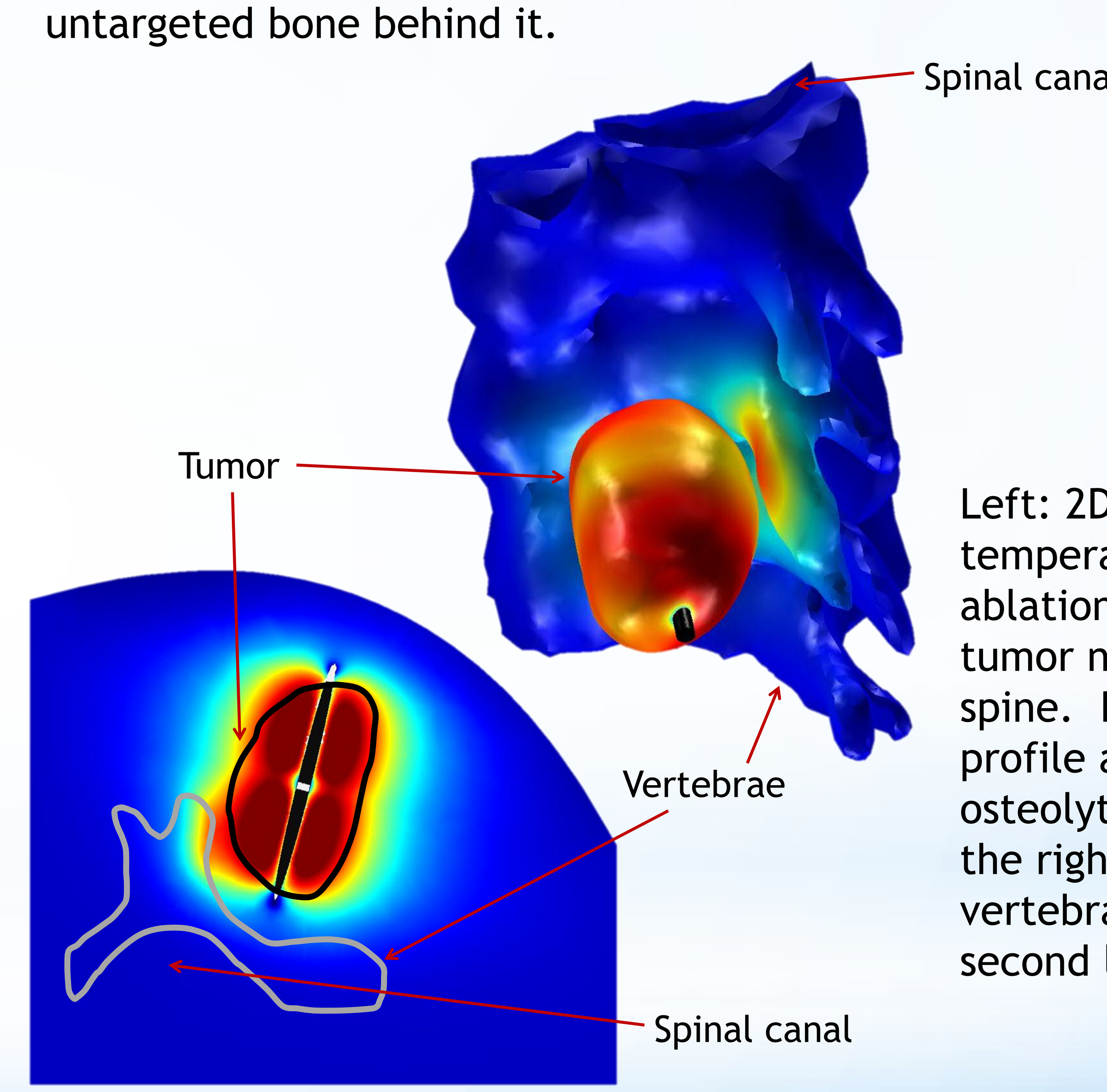
Results



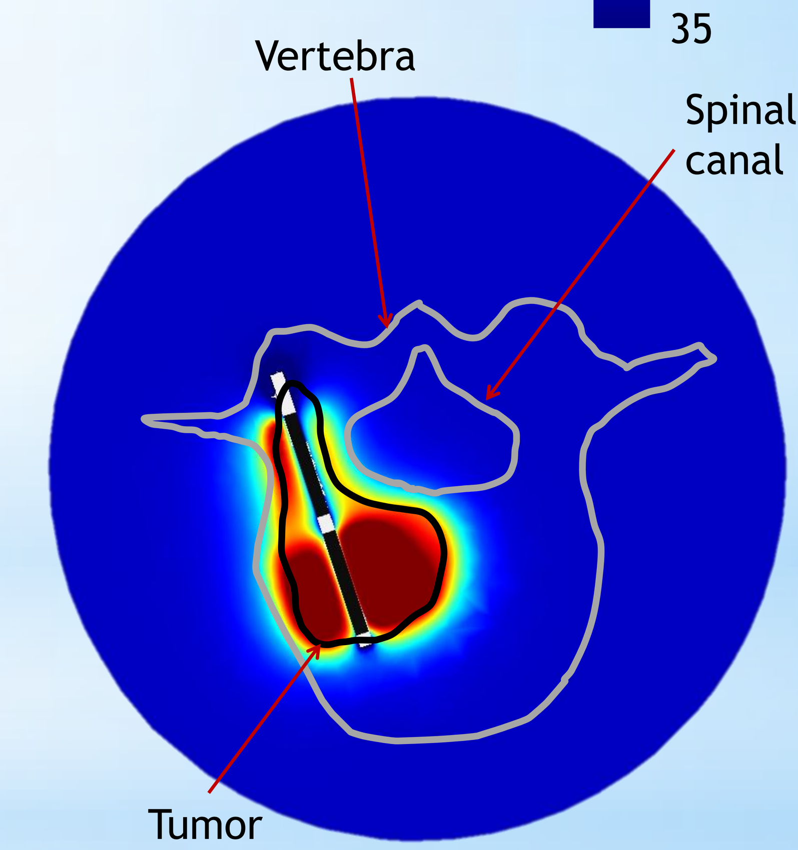


3 applicator configurations were considered for ablating this osteolytic tumor invading the left transverse process of the fifth thoracic vertebra. In B, less power was applied to a 90° sector of the transducer pointing towards the lung. In A and B, the lung reached dangerous temperatures before the posterior portion of the tumor was fully ablated. In C, pictured above and in 3D to the right, the tumor is fully ablated without excessive heating of the lung or untargeted bone behind it.





Left: 2D and 3D temperature profiles after ablation of paraspinal tumor near the cervical spine. Right: Temperature profile after ablation of osteolytic tumor invading the right pedicle and vertebral body of the second lumbar vertebra.



Case	Tumor length	Maximum tumor diameter	Transducer type	Treatment time	Maximum temperature on spinal canal	Minimum temperature on tumor outer boundary	Maximum temperature in tumor
Cervical	3.4 cm	1.8 cm	2 x 1.5 cm, 360°	285 s	39.0°C	54.2°C	71.7°C
Thoracic	2.0 cm	2.2 cm	2 x 1 cm, 360°	300 s	37.3°C	52.0°C	73.9°C
Lumbar	3.8 cm	2.2 cm	2 x 1.5 cm, 120° and 240°	195 s	44.8°C	51.8°C	81.9°C

Summary

Paraspinal and vertebral tumors up to 2.2 cm diameter and 3.8 cm length were heated to lethal temperatures while sparing the spinal cord, and in the thoracic case, the lung and aorta as well. 3D patient-specific models and a treatment planning platform can provide a useful tool for determining the optimal applicator type, applicator location, applied powers, and treatment times. Interstitial ultrasound ablation appears feasible for treating paraspinal and osteolytic vertebral tumors when 3D patient-specific biothermal and acoustic models are applied in treatment planning.

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