J Neurosurg Spine 13:773–779, 2010

Percutaneous computed tomography fluoroscopy–guided conformal ultrasonic ablation of vertebral tumors in a rabbit tumor model

Laboratory investigation

Daniel M. Sciubba, M.D.,[1] E. Clif Burdette, Ph.D.,[3] Jennifer J. Cheng, M.S., M.D.,[1] William A. Pennant, M.S.,[1] Joseph C. Noggle, B.S.,[1] Rory J. Petteys, M.D.,[1] Christopher Alix, M.S.,[3] Chris J. Diederich, Ph.D.,[4] Gabor Fichtinger, Ph.D.,[5] Ziya L. Gokaslan, M.D.,[1] and Kieran P. Murphy, M.D.[1,2]

Departments of [1]Neurosurgery and [2]Interventional Radiology, Johns Hopkins University, Baltimore, Maryland; [3]Systems Research Division, Acoustic MedSystems, Inc., Champaign, Illinois; [4]Department of Radiation Oncology, University of California, San Francisco, California; and [5]Department of Computing, Queen's University, Kingston, Ontario, Canada

Object. Radiofrequency ablation (RFA) has proven to be effective for treatment of malignant and benign tumors in numerous anatomical sites outside the spine. The major challenge of using RFA for spinal tumors is difficulty protecting the spinal cord and nerves from damage. However, conforming ultrasound energy to match the exact anatomy of the tumor may provide successful ablation in such sensitive locations. In a rabbit model of vertebral body tumor, the authors have successfully ablated tumors using an acoustic ablator placed percutaneously via computed tomography fluoroscopic (CTF) guidance.

Methods. Using CTF guidance, 12 adult male New Zealand White rabbits were injected with VX2 carcinoma cells in the lowest lumbar vertebral body. At 21 days, a bone biopsy needle was placed into the geographical center of the lesion, down which an acoustic ablator was inserted. Three multisensor thermocouple arrays were placed around the lesion to provide measurement of tissue temperature during ablation, at thermal doses ranging from 100 to 1,000,000 TEM (thermal equivalent minutes at 43°C), and tumor volumes were given a tumoricidal dose of acoustic energy. Animals were monitored for 24 hours and then sacrificed. Pathological specimens were obtained to determine the extent of tumor death and surrounding tissue damage. Measured temperature distributions were used to reconstruct volumetric doses of energy delivered to tumor tissue, and such data were correlated with pathological findings.

Results. All rabbits were successfully implanted with VX2 cells, leading to a grossly apparent spinal and paraspinal tissue mass. The CTF guidance provided accurate placement of the acoustic ablator in all tumors, as corroborated through gross and microscopic histology. Significant tumor death was noted in all specimens without collateral damage to nearby nerve tissue. Tissue destruction just beyond the margin of the tumor was noted in some but not all specimens. No neurological deficits occurred in response to ablation. Reconstruction of measured temperature data allowed accurate assessment of volumetric dose delivered to tissues.

Conclusions. Using a rabbit intravertebral tumor model, the authors have successfully delivered tumoricidal doses of acoustic energy via a therapeutic ultrasound ablation probe placed percutaneously with CTF guidance. The authors have thus established the first technical and preclinical feasibility study of controlled ultrasound ablation of spinal tumors in vivo. *(DOI: 10.3171/2010.5.SPINE09266)*

Key Words • tumor • spine • ultrasonic ablation • high-intensity ultrasound

Primary and metastatic bone cancer and multiple myeloma affect over 600,000 people every year in the US and cause progressive bone destruction that may result in debilitating pain, fractures, and the inability to walk.[7,33,34,63,66] Surgical options may involve significantly invasive interventions such as corpectomy and/or multilevel instrumented fixations with the potential for extended postprocedural recovery and high rates of surgical morbidity and mortality.[11,27,46,51,59,60] In addition, multifocal vertebral lesions are common and may not be

Abbreviations used in this paper: CTF = CT fluoroscopic; HIFU = high-intensity focused ultrasound; HIIU = high-intensity interstitial ultrasound; RFA = radiofrequency ablation.

amenable to surgical treatment.[2,8,10] Unfortunately, for patients with tumoral spine disease, there is currently no adequate alternative to the immediate pain relief that may occur with minimally invasive percutaneous vertebroplasty.[9,12,20,42,44,47,64] However, such vertebroplasty, at best, only affects pain symptoms and has not been designed to eradicate the cancer.[9,12,20,44,47]

Radiofrequency ablation has proven to be an effective method for the treatment of malignant and benign tumors.[3,24,50,58,67] It works through the application of a current that generates thermal energy and causes localized cellular damage, coagulation, and necrosis at temperatures above 60°C.[19,28,29,57] This technique has been used in several organs and is receiving increasing attention for the treatment of musculoskeletal diseases, such as osteoid osteomas, chondroblastomas, epithelioid hemangioendotheliomas, and bone metastasis, including spinal lesions in rare reports.[4,18,26,43,45,52,62,65] High-intensity interstitial ultrasound is a more recently developed thermal ablation technology that allows for the delivery of ultrasound treatment to deeply seated tumors that are not accessible to the more commonly used extracorporeal HIFU.[13–17,55] In addition, HIIU provides advantages over conventional RFA in terms of its penetration depth, coagulation speed, directionality, and accuracy of thermal lesion size.[15]

The major challenge of using thermal ablation for spinal tumors, however, is the difficulty of protecting the spinal cord and nerves from damage if energy is applied close to the posterior vertebral body wall or in epidural tissue. Conforming ultrasound energy to the exact anatomy of the tumor may provide successful ablation in such sensitive locations, but it first requires accurate image guidance. Computed tomography fluoroscopy may offer a viable solution by providing real-time visualization of the needle or catheter throughout the procedure.[5,31] In the present experiment we postulated that thermal HIIU ablation can be safe and efficacious in the management of metastatic spine cancer. Toward proving this hypothesis, we outline our mechanism and approach by which conformal ultrasound ablation is safely delivered in a minimally invasive manner under CTF guidance in a rabbit spinal tumor model.

Methods

The animal model of spinal tumor in New Zealand White rabbits and rabbit VX2 cells has been previously described.[1] Using CTF guidance, we injected 12 adult male rabbits with a 20-µl suspension containing 400,000 cells of VX2 carcinoma in the lowest lumbar vertebral body. Lower-extremity motor function was assessed daily, using the neurological grading system for rabbits described by Fowl et al.[21] (Grade 0, complete paralysis; Grade 1, partial deficit; and Grade 2, no deficit). At 21 days, the rabbits underwent CT scanning to corroborate the growth of the tumor. Following radiographic assessment of the anatomy of the lesions, each rabbit underwent ultrasonic ablation. Specifically, for each lesion, a bone biopsy needle was placed into the geographical center of the lesion or at the edge of the lesion adjacent to vertebrae. This needle served as the working channel for the acoustic ablator (Fig. 1). The ablator energy pattern was either 360° circumferential or 180° directional. Following corroboration of ideal needle position with CTF guidance, 3 multisensor thermocouple

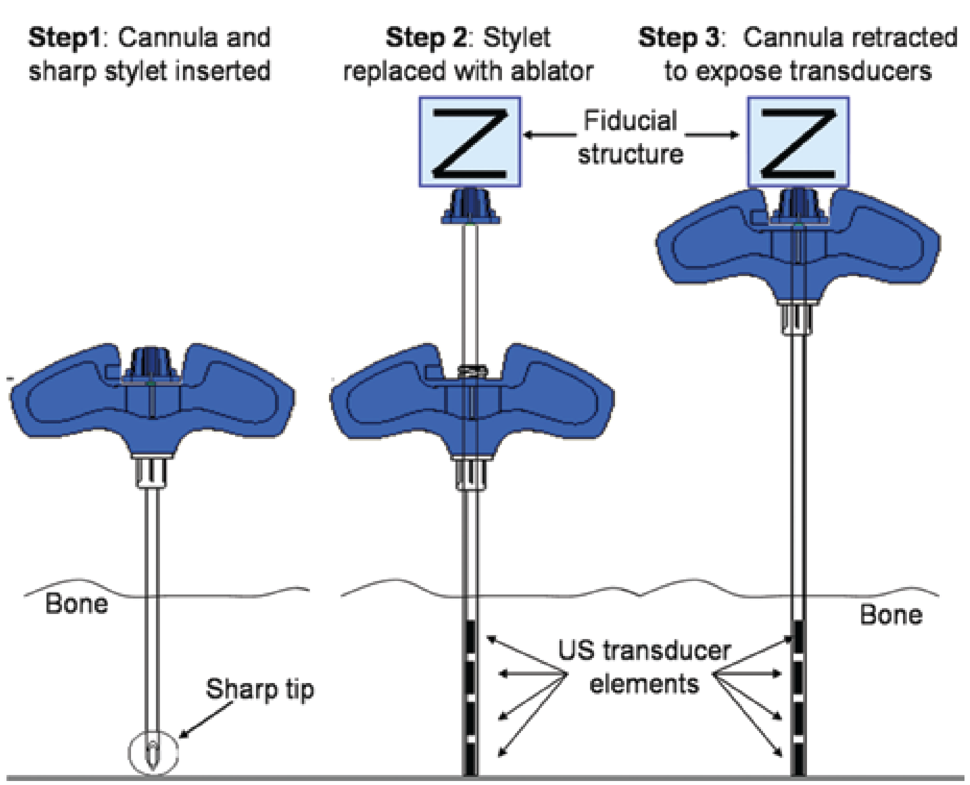

Fig. 1. Illustration of percutaneous trochar and acoustic ablator insertion into vertebral body. US = ultrasound.

arrays were placed around the lesion to provide measurements of tissue temperature during ablation. Computed tomography scanning was again conducted to determine the spatial relationship of the implanted hardware with respect to the location and anatomy of the tumor (Fig. 2).

A single 360° or 180° radial acoustic ablator was then inserted down the working channel of the biopsy needle. Using temperature measurements from the implanted thermocouples, the tumor volumes were given an average of 10 minutes of treatment at temperatures of 50°–70°C, a necrosing tumoricidal dose. All animals were monitored for 24 hours to determine immediate and acute procedure-related morbidity and then were killed using an intravenous euthanasia solution in accordance with our institutional Animal Welfare and Safety Committee guidelines. Tissue samples containing tumor and peritumoral bone and soft tissue were harvested, sectioned, and stained to determine extent of tumor death and surrounding tissue damage. Temperature distribution data were used to reconstruct volumetric thermal dose delivered to tumor tissue, and the findings were spatially correlated with pathological findings.

Results

In all 12 rabbits, VX2 cells were successfully implanted, leading to grossly apparent spinal and paraspinal tissue masses. One rabbit was paraplegic on Day 21 prior to ablation (Fowl neurological Grade 0) due to tumor impingement on the spinal cord and was killed immediately following the ablative procedure. All other animals underwent ablation with no immediate or acute complications, all could walk immediately following the procedure, and all were assigned pre- and postoperative Fowl neurological grades of 2. Computed tomography fluoroscopic guidance provided accurate placement of the acoustic ablator in all tumors, as corroborated on gross and microscopic histological inspection (Fig. 3). To further define the anatomical relationship of the ablator, acoustic energy field, and tumor volume, 3D reconstructions were created using data from the temperature probes and histological and radiographic information. Furthermore, significant tumor death (> 90% assessed cross sectionally) was noted in all specimens without collateral damage to nearby nerve tissue. Marginal death—that is, tissue destruction just beyond the margin of the tumor—was noted in some, but not all, specimens. Reconstruction of temperature distribution data allowed accurate assessment of volumetric thermal dose delivered to tissues (Fig. 4).

Discussion

Current methods of surgical treatment for spinal

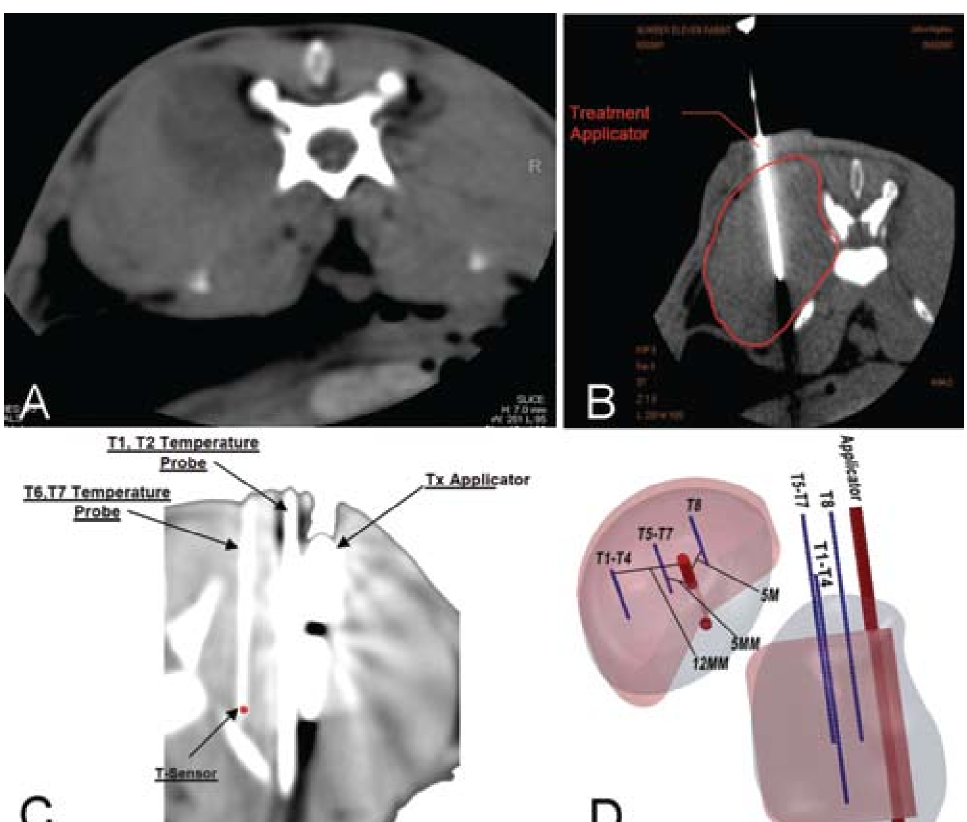

Fig. 2. **A:** Representative CT scan (CT) of paravertebral tumor localization. **B:** Insertion of trochar and acoustic ablator into the tumor mass under CTF guidance. **C:** The CTF image of ablator and temperature probe insertion into tumor mass. **D:** Three-dimensional reconstruction of the anatomical relationship of the ablator and temperature probes within the histologically confirmed tumor *(gray)* and the acoustic energy field *(red)*, the volume of which was determined from temperature probe data.

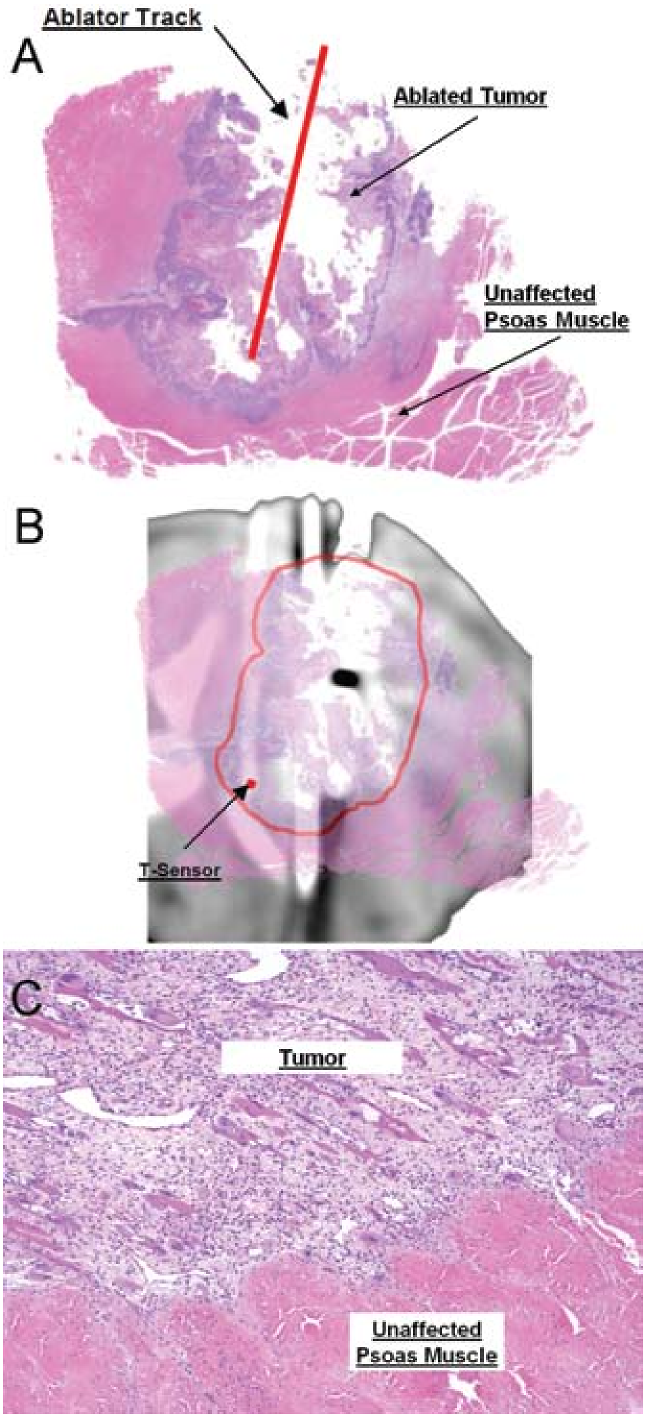

Fig. 3. **A:** Gross histological specimen after acoustic ablation confirming accurate placement of the ablator probe into the tumor mass with the probe tract clearly visible. **B:** Overlay of gross histological specimen and CTF image demonstrating placement of the ablator into the tumor mass. **C:** Photomicrograph demonstrating the presence of ablated tumor tissue next to unaffected muscle tissue. H & E, magnification × 100. T-sensor = temperature sensor.

column neoplastic disease consist of highly invasive procedures, such as vertebrectomy or corpectomy with complex spinal reconstruction, which aim to achieve substantial tumor removal and spinal column stabilization but carry inherent risks due to their duration, complexity, and associated surgical and neurological morbidities. Percutaneous vertebroplasty provides a minimally invasive alternative that can swiftly and adequately treat symptoms, but has high rates of tumor persistence. Radiofrequency ablation has been used successfully to treat a variety of solid tumors in other organs and has the potential to provide tumor control while still remaining minimally invasive. The spinal column, however, presents the challenge of adequately ablating tumors while preserving closely adjacent neural structures. We hope to overcome such a treatment barrier by combining HIIU applicators with CTF guidance for accurate placement of the directional ultrasound therapy probe and, therefore, more spatially precise and targeted delivery of the HIIU to the tumor. In this study, we used an animal model to test the feasibility of CTF-guided HIIU for vertebral neoplasms.

In this current study, rabbit VX2 carcinoma cells were implanted under CTF guidance into the lowest lumbar vertebral body in each of 12 adult male New Zealand White rabbits. This led to the successful growth of a vertebral mass involving paravertebral tissue in all rabbits, as confirmed by CT scanning on Day 21. After imaging on Day 21, each of the rabbits underwent ultrasound ablation procedures, after which there were no acute adverse events, and no paraplegia was noted. Histological analysis of tumor and peritumoral tissue demonstrated significant tumor death in all of the specimens as well as no significant damage to adjacent neural structures. Furthermore, temperature distribution measurements allowed for the spatial reconstruction of thermal dose delivery to each tumor volume.

One rabbit experienced paraplegia prior to tumor ablation. It is important to note that the rabbit spinal cord traverses the entire length of its lumbar spine, in contrast to the human L1–2 conus medullaris. The variance between rabbit and human anatomy should be considered when interpreting neurological outcomes from this experimental model. To establish a context for future projects, it is also important to clarify that acoustic ablation necrotizes the tumor but does not measurably alter the tumor's mass. Therefore, immediate improvement in neurological function would not be expected in an impaired individual, as this would require a reduction in gross tumor size. Such a scenario does not pertain to the current study, as all but one animal suffered no neurological deficits prior to ablation.

In 1960, Fry and Fry[23] were the first to describe the use of high-intensity ultrasound technology for neurosurgical applications. High-intensity focused ultrasound has since gained popularity as a treatment modality for prostate cancer, with recurrence-free survival outcomes nearing those of radiation therapy.[53] Lafon et al.[35–38,40,41] and Diederich et al.[16] have pioneered the development of interstitial ultrasound applicators, or HIIU, now being investigated in animal models for use in the ablation of liver tumors, as well as for the endoscopic ablation of esophageal and other gastrointestinal tract malignancies.[15,35–38,40,41,55] High-intensity interstitial ultrasound is a promising technology for the ablation of spinal tumors that are inaccessible to HIFU and are poor candidates for RFA because of their proximity to sensitive neurological structures.[39,49] Because it is less invasive than percutane-

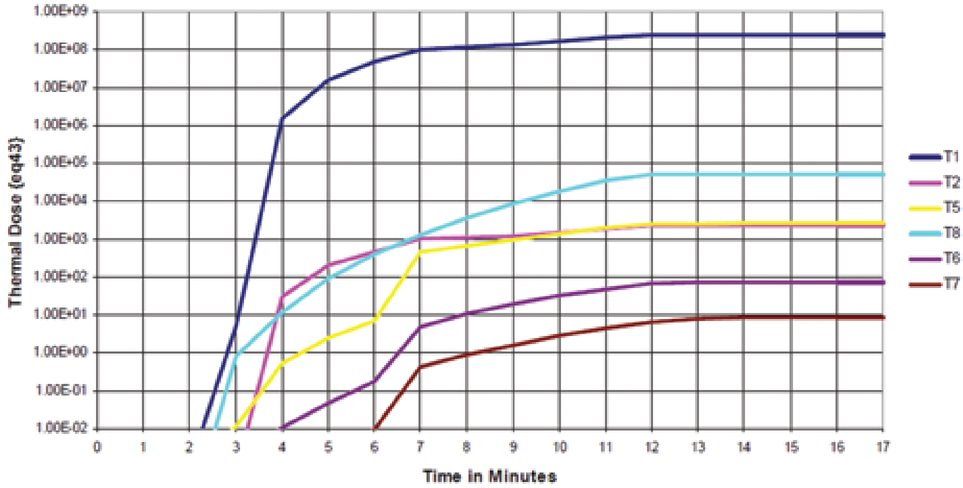

Fig. 4. Graph demonstrating temperature distribution and maximal volumetric thermal dose delivered to target tissues measured by the temperature probes.

ous vertebroplasty, HIIU offers the possibility of complete or curative tumor ablation. Its potentially superior control of ablation size and shape permits avoidance of collateral damage to surrounding tissues, such as may arise when using RFA.

An important component of this study was the use of CTF to guide HIIU applicator placement. Computed tomography fluoroscopic guidance improves on CT imaging by providing image acquisition and reconstruction at 6–8 frames per second or nearly real-time speed.[22] First introduced by Katada et al.[30,31] in 1993, the technology has been most commonly used for percutaneous interventional procedures such as biopsy and abscess drainage in the thorax and abdomen, as well as for various surgical procedures throughout the body, including drainage of intracranial hematomas. Some investigators have reported potential benefits such as decreased needle placement time, decreased overall procedure time, decreased patient radiation exposure, and improved diagnostic accuracy compared with conventional CT-guided procedures.[5,25,32,56] Computed tomography fluoroscopic guidance has also been shown to have benefits when used in spinal procedures such as percutaneous vertebroplasty, and it has been used for various procedures including RFA treatment of bone metastases and percutaneous spinal fixation procedures.[6,26,54] In this study, we demonstrated the successful use of CTF to provide real-time guidance for the accurate placement of the HIIU applicators into tumors.

Using the rabbit intravertebral tumor model developed at our institution, we have been able to successfully deliver tumoricidal doses of acoustic energy via an RFA probe that was placed percutaneously with CTF guidance. In this way, we established the technical and preclinical feasibility of controlled ultrasound ablation of spinal tumors in vivo. Data from this initial set of animals are being integrated into a rabbit-based navigation software system. The next set of animal experiments will involve additional technical developments including frameless anatomical imaging (Fig. 5), the integration of enhanced tumor imaging, and modified acoustic ablators capable of more accurate energy delivery.[14,48,61]

Conclusions

Use of an HIIU ablation probe placed via CTF guidance successfully killed tumor cells in a rabbit spine tumor model without leading to collateral neurological damage. From these initial experiments, we hope to develop a family of HIIU ablators that, according to measured physical parameters, are expected to be appropriate for conformal ultrasound ablation of primary and metastatic spinal tumors in humans.

Disclosure

Dr. Gokaslan owns stock in Spinal Kinetics and US Spine; receives clinical or research support from AO North America, Medtronic, DePuy, and Integra; and receives fellowship support and an honorarium from AO North America, where he is also a board member. Dr. Sciubba receives an honorarium from DePuy Spine. Dr. Diederich is the inventor and patent holder of the technology described in this study.

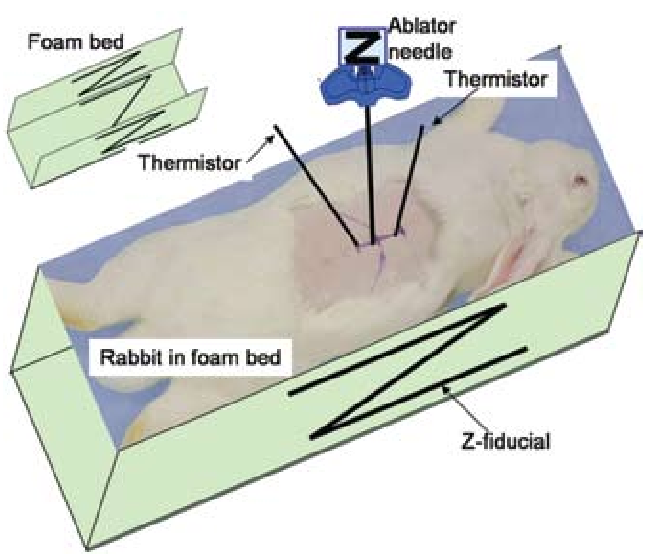

Fig. 5. Illustration of interstitial ablation technique using a rabbit-based navigation system that will allow imaging of the spine without external fixation.

Author contributions to the study and manuscript preparation include the following. Conception and design: Sciubba, Burdette, Alix, Fichtinger, Diederich, Gokaslan, Murphy. Experimental work: Sciubba, Burdette, Pennant, Alix, Murphy. Acquisition of data: Sciubba, Burdette, Pennant, Noggle, Alix, Murphy. Analysis and interpretation of data: Sciubba, Burdette, Cheng, Pennant, Noggle, Petteys, Alix, Gokaslan, Murphy. Drafting the article: Sciubba, Burdette, Cheng, Noggle, Petteys, Murphy.

References

1. Amundson E, Pradilla G, Brastianos P, Bagley C, Riley LH III, Garonzik IM, et al: A novel intravertebral tumor model in rabbits. **Neurosurgery 57:**341–346, 2005
2. Bilsky MH, Boland PJ, Panageas KS, Woodruff JM, Brennan MF, Healey JH: Intralesional resection of primary and metastatic sarcoma involving the spine: outcome analysis of 59 patients. **Neurosurgery 49:**1277–1286, 2001
3. Burak WE Jr, Agnese DM, Povoski SP, Yanssens TL, Bloom KJ, Wakely PE, et al: Radiofrequency ablation of invasive breast carcinoma followed by delayed surgical excision. **Cancer 98:**1369–1376, 2003
4. Callstrom MR, Charboneau JW, Goetz MP, Rubin J, Wong GY, Sloan JA, et al: Painful metastases involving bone: feasibility of percutaneous CT- and US-guided radio-frequency ablation. **Radiology 224:**87–97, 2002
5. Carlson SK, Bender CE, Classic KL, Zink FE, Quam JP, Ward EM, et al: Benefits and safety of CT fluoroscopy in interventional radiologic procedures. **Radiology 219:**515–520, 2001
6. Caudana R, Renzi Brivio L, Ventura L, Aitini E, Rozzanigo U, Barai G: CT-guided percutaneous vertebroplasty: personal experience in the treatment of osteoporotic fractures and dorsolumbar metastases. **Radiol Med (Torino) 113:**114–133, 2008
7. Chi JH, Bydon A, Hsieh P, Witham T, Wolinsky JP, Gokaslan ZL: Epidemiology and demographics for primary vertebral tumors. **Neurosurg Clin N Am 19:**1–4, 2008
8. Chi JH, Sciubba DM, Rhines LD, Gokaslan ZL: Surgery for primary vertebral tumors: en bloc versus intralesional resection. **Neurosurg Clin N Am 19:**111–117, 2008
9. Chiras J, Depriester C, Weill A, Sola-Martinez MT, Deramond H: [Percutaneous vertebral surgery. Technics and indications.] **J Neuroradiol 24:**45–59, 1997 (Fr)
10. Cook AM, Lau TN, Tomlinson MJ, Vaidya M, Wakeley CJ, Goddard P: Magnetic resonance imaging of the whole spine in suspected malignant spinal cord compression: impact on management. **Clin Oncol (R Coll Radiol) 10:**39–43, 1998
11. Cooper PR, Errico TJ, Martin R, Crawford B, DiBartolo T: A systematic approach to spinal reconstruction after anterior decompression for neoplastic disease of the thoracic and lumbar spine. **Neurosurgery 32:**1–8, 1993
12. Cotten A, Dewatre F, Cortet B, Assaker R, Leblond D, Duquesnoy B, et al: Percutaneous vertebroplasty for osteolytic metastases and myeloma: effects of the percentage of lesion filling and the leakage of methyl methacrylate at clinical follow-up. **Radiology 200:**525–530, 1996
13. Deardorff DL, Diederich CJ: Angular directivity of thermal coagulation using air-cooled direct-coupled interstitial ultrasound applicators. **Ultrasound Med Biol 25:**609–622, 1999
14. Deardorff DL, Diederich CJ: Axial control of thermal coagulation using a multi-element interstitial ultrasound applicator with internal cooling. **IEEE Trans Ultrason Ferroelectr Freq Control 47:**170–178, 2000
15. Delabrousse E, Mithieux F, Birer A, Salomir R, Chapelon J, Lafon C: [Ultrasound interstitial mini invasive probes for thermal ablation in liver: feasibility study in vivo.] **J Radiol 88:**1817–1822, 2007 (Fr)
16. Diederich CJ, Nau WH, Burdette EC, Bustany IS, Deardorff DL, Stauffer PR: Combination of transurethral and interstitial ultrasound applicators for high-temperature prostate thermal therapy. **Int J Hyperthermia 16:**385–403, 2000
17. Diederich CJ, Stafford RJ, Nau WH, Burdette EC, Price RE, Hazle JD: Transurethral ultrasound applicators with directional heating patterns for prostate thermal therapy: in vivo evaluation using magnetic resonance thermometry. **Med Phys 31:**405–413, 2004
18. Dupuy DE, Hong R, Oliver B, Goldberg SN: Radiofrequency ablation of spinal tumors: temperature distribution in the spinal canal. **AJR Am J Roentgenol 175:**1263–1266, 2000
19. Finelli A, Rewcastle JC, Jewett MA: Cryotherapy and radiofrequency ablation: pathophysiologic basis and laboratory studies. **Curr Opin Urol 13:**187–191, 2003
20. Fourney DR, Schomer DF, Nader R, Chlan-Fourney J, Suki D, Ahrar K, et al: Percutaneous vertebroplasty and kyphoplasty for painful vertebral body fractures in cancer patients. **J Neurosurg 98 (1 Suppl):**21–30, 2003
21. Fowl RJ, Patterson RB, Gewirtz RJ, Anderson DK: Protection against postischemic spinal cord injury using a new 21-aminosteroid. **J Surg Res 48:**597–600, 1990
22. Froelich JJ, Wagner HJ: CT-fluoroscopy: Tool or gimmick? **Cardiovasc Intervent Radiol 24:**297–305, 2001
23. Fry WJ, Fry FJ: Fundamental neurological research and human neurosurgery using intense ultrasound. **IRE Trans Med Electron ME-7:**166–181, 1960
24. Garrean S, Hering J, Saied A, Helton WS, Espat NJ: Radiofrequency ablation of primary and metastatic liver tumors: a critical review of the literature. **Am J Surg 195:**508–520, 2008
25. Gianfelice D, Lepanto L, Perreault P, Chartrand-Lefebvre C, Milette PC: Value of CT fluoroscopy for percutaneous biopsy procedures. **J Vasc Interv Radiol 11:**879–884, 2000
26. Goetz MP, Callstrom MR, Charboneau JW, Farrell MA, Maus TP, Welch TJ, et al: Percutaneous image-guided radiofrequency ablation of painful metastases involving bone: a multicenter study. **J Clin Oncol 22:**300–306, 2004
27. Gokaslan ZL, York JE, Walsh GL, McCutcheon IE, Lang FF, Putnam JB Jr, et al: Transthoracic vertebrectomy for metastatic spinal tumors. **J Neurosurg 89:**599–609, 1998
28. Hsu TH, Fidler ME, Gill IS: Radiofrequency ablation of the kidney: acute and chronic histology in porcine model. **Urology 56:**872–875, 2000
29. Itoh T, Orba Y, Takei H, Ishida Y, Saitoh M, Nakamura H, et al: Immunohistochemical detection of hepatocellular carcinoma in the setting of ongoing necrosis after radiofrequency ablation. **Mod Pathol 15:**110–115, 2002
30. Katada K, Anno H, Takeshita G, Ogura Y, Koga S, Ida Y, et al: [Development of real-time CT fluoroscopy.] **Nippon Igaku Hoshasen Gakkai Zasshi 54:**1172–1174, 1994 (Jpn)
31. Katada K, Kato R, Anno H, Ogura Y, Koga S, Ida Y, et al: Guidance with real-time CT fluoroscopy: early clinical experience. **Radiology 200:**851–856, 1996
32. Kirchner J, Kickuth R, Laufer U, Schilling EM, Adams S, Liermann D: CT fluoroscopy-assisted puncture of thoracic and abdominal masses: a randomized trial. **Clin Radiol 57:**188–192, 2002
33. Klimo P Jr, Schmidt MH: Surgical management of spinal metastases. **Oncologist 9:**188–196, 2004
34. Kyle RA, Rajkumar SV: Epidemiology of the plasma-cell disorders. **Best Pract Res Clin Haematol 20:**637–664, 2007
35. Lafon C, Chapelon JY, Prat F, Gorry F, Margonari J, Theillère Y, et al: Design and preliminary results of an ultrasound applicator for interstitial thermal coagulation. **Ultrasound Med Biol 24:**113–122, 1998
36. Lafon C, Chapelon JY, Prat F, Gorry F, Theillère Y, Cathignol D: Design and in vitro results of a high intensity ultrasound interstitial applicator. **Ultrasonics 36:**683–687, 1998
37. Lafon C, Chavrier F, Prat F, Chapelon JY, Cathignol D: Theoretical comparison of two interstitial ultrasound applicators designed to induce cylindrical zones of tissue ablation. **Med Biol Eng Comput 37:**298–303, 1999

38. Lafon C, Melo de Lima D, Theillère Y, Prat F, Chapelon JY, Cathignol D: Optimizing the shape of ultrasound transducers for interstitial thermal ablation. **Med Phys 29:**290–297, 2002
39. Lafon C, Melodelima D, Salomir R, Chapelon JY: Interstitial devices for minimally invasive thermal ablation by high-intensity ultrasound. **Int J Hyperthermia 23:**153–163, 2007
40. Lafon C, Salomir R, Bouchoux G, Birer A, Owen N, Delabrousse E, et al: Ultrasound interstitial applicators for thermal ablation in liver. **J Acoust Soc Am 123:**2996, 2008
41. Lafon C, Theillére Y, Prat F, Arefiev A, Chapelon JY, Cathignol D: Development of an interstitial ultrasound applicator for endoscopic procedures: animal experimentation. **Ultrasound Med Biol 26:**669–675, 2000
42. Levine SA, Perin LA, Hayes D, Hayes WS: An evidence-based evaluation of percutaneous vertebroplasty. **Manag Care 9:** 56–60, 63, 2000
43. Lindner NJ, Ozaki T, Roedl R, Gosheger G, Winkelmann W, Wörtler K: Percutaneous radiofrequency ablation in osteoid osteoma. **J Bone Joint Surg Br 83:**391–396, 2001
44. Martin JB, Jean B, Sugiu K, San Millán Ruíz D, Piotin M, Murphy K, et al: Vertebroplasty: clinical experience and follow-up results. **Bone 25 (2 Suppl):**11S–15S, 1999
45. Maruyama M, Asano T, Kenmochi T, Kainuma O, Iwasaki K, Miyauchi H, et al: Radiofrequency ablation therapy for bone metastasis from hepatocellular carcinoma: case report. **Anticancer Res 23 (3C):**2987–2989, 2003
46. Melcher I, Disch AC, Khodadadyan-Klostermann C, Tohtz S, Smolny M, Stöckle U, et al: Primary malignant bone tumors and solitary metastases of the thoracolumbar spine: results by management with total en bloc spondylectomy. **Eur Spine J 16:**1193–1202, 2007
47. Murphy KJ, Deramond H: Percutaneous vertebroplasty in benign and malignant disease. **Neuroimaging Clin N Am 10:** 535–545, 2000
48. Nau WH, Diederich CJ, Burdette EC: Evaluation of multielement catheter-cooled interstitial ultrasound applicators for high-temperature thermal therapy. **Med Phys 28:**1525–1534, 2001
49. Nau WH, Diederich CJ, Shu R: Feasibility of using interstitial ultrasound for intradiscal thermal therapy: a study in human cadaver lumbar discs. **Phys Med Biol 50:**2807–2821, 2005
50. Neeman Z, Wood BJ: Radiofrequency ablation beyond the liver. **Tech Vasc Interv Radiol 5:**156–163, 2002
51. Olsen MA, Mayfield J, Lauryssen C, Polish LB, Jones M, Vest J, et al: Risk factors for surgical site infection in spinal surgery. **J Neurosurg 98 (2 Suppl):**149–155, 2003
52. Rosenthal DI, Hornicek FJ, Torriani M, Gebhardt MC, Mankin HJ: Osteoid osteoma: percutaneous treatment with radiofrequency energy. **Radiology 229:**171–175, 2003
53. Rouvière O, Souchon R, Salomir R, Gelet A, Chapelon JY, Lyonnet D: Transrectal high-intensity focused ultrasound ablation of prostate cancer: effective treatment requiring accurate imaging. **Eur J Radiol 63:**317–327, 2007
54. Sciubba DM, Wolinsky JP, Than KD, Gokaslan ZL, Witham TF, Murphy KP: CT fluoroscopically guided percutaneous placement of transiliosacral rod for sacral insufficiency fracture: case report and technique. **AJNR Am J Neuroradiol 28:** 1451–1454, 2007
55. Seket B, Lafon C, Mithieux F, Goldenstedt C, Paquet C, Chapelon JY, et al: Developing an interstitial ultrasound applicator for thermal ablation in liver: results of animal experiments. **J Surg Res 142:**81–89, 2007
56. Silverman SG, Tuncali K, Adams DF, Nawfel RD, Zou KH, Judy PF: CT fluoroscopy-guided abdominal interventions: techniques, results, and radiation exposure. **Radiology 212:** 673–681, 1999
57. Solbiati L: New applications of ultrasonography: interventional ultrasound. **Eur J Radiol 27 (Suppl 2):**S200–S206, 1998
58. Stone MJ, Venkatesan AM, Locklin J, Pinto P, Linehan M, Wood BJ: Radiofrequency ablation of renal tumors. **Tech Vasc Interv Radiol 10:**132–139, 2007
59. Sundaresan N, Rothman A, Manhart K, Kelliher K: Surgery for solitary metastases of the spine: rationale and results of treatment. **Spine 27:**1802–1806, 2002
60. Tomita K, Kawahara N, Murakami H, Demura S: Total en bloc spondylectomy for spinal tumors: improvement of the technique and its associated basic background. **J Orthop Sci 11:**3–12, 2006
61. Underwood HR, Burdette EC, Ocheltree KB, Magin RL: A multi-element ultrasonic hyperthermia applicator with independent element control. **Int J Hyperthermia 3:**257–267, 1987
62. Venbrux AC, Montague BJ, Murphy KP, Bobonis LA, Washington SB, Soltes AP, et al: Image-guided percutaneous radiofrequency ablation for osteoid osteomas. **J Vasc Interv Radiol 14:**375–380, 2003
63. Weber K, Damron TA, Frassica FJ, Sim FH: Malignant bone tumors. **Instr Course Lect 57:**673–688, 2008
64. Weill A, Chiras J, Simon JM, Rose M, Sola-Martinez T, Enkaoua E: Spinal metastases: indications for and results of percutaneous injection of acrylic surgical cement. **Radiology 199:**241–247, 1996
65. Woertler K, Vestring T, Boettner F, Winkelmann W, Heindel W, Lindner N: Osteoid osteoma: CT-guided percutaneous radiofrequency ablation and follow-up in 47 patients. **J Vasc Interv Radiol 12:**717–722, 2001
66. Wong DA, Fornasier VL, MacNab I: Spinal metastases: the obvious, the occult, and the impostors. **Spine 15:**1–4, 1990
67. Zhu JC, Yan TD, Morris DL: A systematic review of radiofrequency ablation for lung tumors. **Ann Surg Oncol 15:**1765–1774, 2008

Manuscript submitted March 26, 2009.
Accepted May 25, 2010.
Address correspondence to: Daniel M. Sciubba, M.D., Department of Neurosurgery, Johns Hopkins University, 600 North Wolfe Street, Meyer Building 8-161, Baltimore, Maryland 21287. email: dsciubb1@jhmi.edu.