

マルチモダリティ化により異なる物理量の組合せを画像化するため死角を減らせ、さらに安全性確保のための種々の確認方法が可能となるなど非常に大きな意義がある。特にMRIとの組合せは組織画像、温度画像や機能画像 (*f*-MRI) 画像の取得も可能となるため、今後の新発見展開が期待される。

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## 参考文献

- (1) Lynn JG, Zwemmer RL, Chick AJ, Miller AF. A new method for the generation and use of focused ultrasound in experimental biology. *J Gen Physiol* 1942; 26: 179-193.
- (2) Williams AR. *Ultrasound: biological effects and potential hazards*. Academic Press 1983: 95.
- (3) Vaezy S, Shi X, Martin RW, Chi E, Nelson PI, Bailey MR, Crum LA. Real-time visualization of high-intensity focused ultrasound treatment using ultrasound imaging. *Ultrasound Med Biol* 2001; 27(1): 33-42.
- (4) Seip R, Ebbini ES. Noninvasive estimation of tissue temperature response to heating fields using diagnostic ultrasound. *IEEE Trans Biomed Eng* 1995; 42(8): 828-839.
- (5) Miller NR, Bamber JC, Meaney PM. Fundamental limitations of noninvasive temperature imaging by means of ultrasound echo strain estimation. *Ultrasound Med Biol* 2002; 28(10): 1319-1333.
- (6) Azuma T, Sasaki K, Kawabata K, Umemura S. Radiation force imaging for detection of irreversible change caused by high intensity focused ultrasound therapy. *Proc IEEE Ultrason Sympo* 2005: 1245-1248.
- (7) 立花俊郎, 古賀悦子. ウロキナーゼのブースターとしての超音波応用. *血液と脈管* 1981; 12: 450-453.
- (8) 古幡 博, 原 正忠, 金江 清. 血栓溶解・超音波複合作用による血栓溶解効果増強に関する研究 (抄録). *バイオレオロジー学会* 1987; 46.
- (9) Kudo S. Thrombolysis with with ultrasound effect. *Tokyo Jikeikai Med J* 1989; 101: 1005-1012.
- (10) Cohen MG, Tuero E, Bluguermann J, Kevorkian R, Berrocal DH, Carlevaro O, Picabea E, Hudson MP, Siegel RJ, Douthat L, Greenbaum AB, Echt D, Douglas Weaver W, Grinfeld LR. Transcutaneous ultrasound-facilitated coronary thrombolysis during acute myocardial infarction. *Am J Cardiol* 2003; 92: 454-457.
- (11) Hacke W, Kaste M, Bluhmki E, Brozman M, Dávalos A, Guidetti D, Larrue V, Lees KR, Medeghri Z, Machnig T, Schneider D, von Kummer R, Wahlgren N, Toni D. Thrombolysis with alteplase 3 to 4.5 hours after acute ischemic stroke. *N Engl J Med* 2008; 359: 1317-1329.
- (12) Cintas P, Traon APL, Larrue V. High rate of recanalization of middle cerebral artery occlusion during 2-MHz transcranial color-coded Doppler continuous monitoring without thrombolytic drug. *Stroke* 2002; 33(2): 626-628.
- (13) Eggers J, König IR, Koch B, Händler G, Seidel G. Sonothrombolysis with transcranial color-coded sonography and recombinant tissue-type plasminogen activator in acute middle cerebral artery main stem occlusion: results from a randomized study. *Stroke* 2008; 39: 1470-1475.
- (14) Alexandrov AV, Molina CA, Grotta JC, Garami Z, Ford SR, Alvarez-Sabin J, Montaner J, Saqqur

- M, Demchuk AM, Moyé LA, Hill MD, Wojner AW. Ultrasound-enhanced systemic thrombolysis for acute ischemic stroke. *N Engl J Med* 2004; 351: 2170-2178.
- (15) Molina CA, Ribo M, Rubiera M, Montaner J, Santamarina E, Delgado-Mederos R, Arenillas JF, Huertas R, Purroy F, Delgado P, Alvarez-Sabin J. Microbubble administration accelerates clot lysis during continuous 2-MHz ultrasound monitoring in stroke patients treated with intravenous tissue plasminogen activator. *Stroke* 2006; 34: 425-429.
  - (16) Daffertshofer M, Gass A, Ringleb P, Sitzer M, Sliwka U, Els T, Sedlaczek O, Koroshetz WJ, Hennerici MG. Transcranial low-frequency ultrasound-mediated thrombolysis in brain ischemia; increased risk of hemorrhage with combined ultrasound and tissue plasminogen activator; results of a phase II clinical trial. *Stroke* 2005; 36: 1441-1446.
  - (17) Reinhard M, Hetzel A, Krüger S, Kretzer S, Talazko J, Ziyeh S, Weber J, Els T. Blood-brain barrier disruption by low-frequency ultrasound. *Stroke* 2006; 37: 1546-1548.
  - (18) Aaslid R, Markwalder TM, Nornes H. Noninvasive transcranial Doppler ultrasound recording of flow velocity in basal cerebral arteries. *J Neurosurg* 1982; 57(6): 769-774.
  - (19) 古橋 博. 経頭蓋骨超音波断層法の新展開. *神経超音波医学* 1989; 2: 8-15.
  - (20) 土屋 隆, 矢坂正弘, 山口武典, 長谷川泰弘, 尾前 豪. Transcranial real-time color-flow Doppler による頭蓋内脳血管の描出および血流速度測定を試み. *脳卒中* 1989; 11: 564-571.
  - (21) Pfaffenberger S, Devic-Kuhar B, Kollmann C, Kastl SP, Kaun C, Speidl WS, Weiss TW, Demyanets S, Ullrich R, Sochor H, Wöber C, Zeitlhofer J, Huber K, Gröschl M, Benes E, Maurer G, Wojta J, Gottsauner-Wolf M. Can a commercial diagnostic ultrasound device accelerate thrombolysis? An in vitro skull model. *Stroke* 2005; 36: 124-128.
  - (22) Pernot M, Tanter M, Fink M. 3-D real-time motion correction in high-intensity focused ultrasound therapy. *Ultrasound Med Biol* 2004; 30(9): 1239-1249.
  - (23) Hynynen K, McDannold N, Sheikov NA, Jolesz FA, Vykhodtseva N. Local and reversible blood-brain barrier disruption by noninvasive focused ultrasound at frequencies suitable for trans-skull sonications. *NeuroImage* 2005; 24: 12-20.
  - (24) Ammi AY, Mast TD, Huang IH, Abruzzo TA, Coussios CC, Shaw GJ, Holland CK. Characterization of Ultrasound Propagation Through Ex-vivo Human Temporal Bone. *Ultrasound Med Biol* 2008; 34(10): 1578-1589.
  - (25) Azuma T, Kawabata K, Umemura S, Ogihara M, Kubota J, Sasaki A, Furuhashi H. Bubble generation by standing wave in water surrounded by cranium with transcranial ultrasonic beam. *Jpn J Appl Phys* 2005; 44(6B): 4625-4630.
  - (26) Baron C, Aubry JF, Tanter M, Meairs S, Fink M. Simulation of intracranial acoustic fields in clinical trials of sonothrombolysis. *Ultrasound Med Biol* 2009; 35(7): 1148-1158.
  - (27) Saguchi T, Onoue H, Urashima M, Ishibashi T, Abe T, Furuhashi H. Effective and safe conditions of low-frequency transcranial ultrasonic thrombolysis for acute ischemic stroke: neurologic and histologic evaluation in a rat middle cerebral artery stroke model. *Stroke* 2008; 39: 1007-1011.
  - (28) Oshio K, Shinmoto H. Simulation of US imaging by using a 3D CT data set. *Scientific Assembly and Annual Meeting Program of RSNA 1996*: 517, 703MS.
  - (29) Arai O, Mitake T, Oshio K, Ookuma K, Shinmoto H, Iwasaki T. Integration computer tomography in ultrasound diagnosis named virtual sonography. *Scientific Assembly and Annual Meeting Program of RSNA 2003*: 807, 9424IMA-i.
  - (30) Iwasaki T, Mikami E, Shimosegawa T, Arai O, Mitake T. Real-time virtual sonography: a novel

- navigation tool in percutaneous radiofrequency ablation of hepatocellular carcinomas. Scientific Assembly and Annual Meeting Program of RSNA 2004; 805, 9103DS-i.
- (31) 佐々木明, 荒井 修, 阿部信隆, 仲本秀和, 窪田 純. 超音波診断装置と MRI 装置のマルチモダリティ化検討Ⅱ. 超音波医学 2009; 36(Suppl): S297.
- (32) Azuma T, Kawabata K, Asami R, Umemura S. Tissue coagulation imaging based on Bi-plane Rf cross correlation during high intensity focused ultrasound therapy. IEEE Int Ultrason Sympo 2009: P2-A-09.
- (33) Jakob PM, Hendrich C, Breiting T, Schafer A, Berden A, Haase A. Real time monitoring of laser-induced thermal changes in cartilage in vitro by using snapshot FLASH. Magn Reson Med 1997; 37: 805-808.
- (34) Ishihara Y, Calderon A, Watanabe H, Okamoto K, Suzuki Y, Kuroda K, Suzuki Y. A precise and fast temperature mapping using water proton chemical shift. Magn Reson Med 1995; 34: 814-823.
- (35) 仲本秀和, 安永武史, 橋爪 誠, 伊関 洋. 治療計画と複数ナビゲーションの統合による MRI 誘導下穿刺術の精度向上. 日本コンピュータ外科学会誌 2008; 10(1): 45-52. —
- (36) 佐野耕一, 及川道雄, 磯部義明. リージョングローイング法による軟部組織の抽出と 3 次元表示. Med Imag Tech 1995; 13(3).
- (37) Kass M, Witkin A, Terzopoulos D. Snakes: active contour models. Int J Computer Vision 1988; 1(4): 321-331.
- (38) Malladi R, Sethian JA, Vemuri BC. Shape modeling with front propagation: a level set approach. IEEE Trans Pattern Anal Machine Intell 1995 Feb; 17(2): 158-175.
- (39) Goldberg DE. Genetic algorithm in search, optimization, and machine learning. Addison Wesley 1989.
- (40) 阿部信隆, 荒井 修, 仲本秀和, 窪田 純, 佐々木明. 超音波治療のためのマルチモダリティナビゲーションシステムの開発Ⅰ. 超音波医学 2009; 36(Suppl): S297.
- (41) 阿部信隆, 谷口拓樹, 西村 博, 小林寿光, 垣添忠生. 術中オープン MRI 下での MR 画像における臓器領域抽出. JAMIT 第 25 回大会 2006.
- (42) 荻原 誠, 荒井 修, 窪田 純, 三竹 毅, 佐々木明, 三村秀樹, 古幡 博. 経頭蓋超音波脳血栓溶解治療における brain virtual sonography の可能性. 神経超音波医学 2006 March; 19(Suppl): 65.
- (43) Ogihara M, Arai O, Kubota J, Mitake T, Sasaki A, Mitsumura H, Furuhashi H. Possibility of brain virtual sonography system for the ultrasound thrombolysis system with TCCFI. 神経超音波医学 2006 Sept; 19(2): 88.
- (44) 荻原 誠, 荒井 修, 窪田 純, 佐々木明, 三村秀樹, 古幡 博. Brain virtual sonography の経頭蓋超音波脳血栓溶解治療への適応. 超音波医学 2007; 34(Suppl): S572.

