In Vivo MREIT Conductivity Imaging of Canine Brain to Evaluate Ischemia and Abscess

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***Abstract*—MREIT has reached the stage of *in vivo* animal and human imaging experiments. To support its clinical significance, we should demonstrate that the conductivity image provides meaningful diagnostic information that is not available from other imaging modalities. To investigate any change of electrical conductivity due to brain diseases of ischemia and abscess, we scanned an animal with such a regional brain disease along with a separate prior scan of the same animal having no disease model. Conductivity images shown in this study indicate that time-course variation of conductivity contrast between normal and abnormal regions are distinguishable in a different way compared with conventional MR image techniques.**

Keywords-MREIT, conductivity, ischemia, abscess

I. INTRODUCTION

Magnetic resonance electrical impedance tomography (MREIT) utilizes an MRI scanner to measure magnetic flux density data inside the object induced by externally injected currents [1-5]. The magnetic field induced by an externally injected current disturbs the main B0 field of the MRI scanner and produces extra phase changes in MR phase images. Extracting the phase changes from MR phase images, we can obtain the induced magnetic flux density images to be used in MREIT conductivity image reconstructions [5]. Recent MREIT studies of postmortem and *in vivo* animals and human subjects demonstrated that significant conductivity contrasts exist among different tissues and organs [6-8].

Given a noise level of the MRI scanner with an adopted imaging method including RF coils and pulse sequence, the quality of a reconstructed conductivity image depends on the amount of injection currents. We should, however, limit it to a level where possible side effects such as nerve stimulations are negligible compared with any clinical significance of the method. This imposes a technical challenge of minimizing the noise level in MR phase images.

Technical developments in MREIT to improve the measurement sensitivity must be also accompanied by experimental validation studies to support its clinical significance. In this paper, we address this issue and describe our recent *in vivo* animal imaging studies. Adopting all the latest methodological improvements such as carbon-hydrogel electrodes, low-noise constant current source and multi-echo pulse sequence, we have performed *in vivo* animal imaging studies to investigate any change of electrical conductivity due to brain ischemia and abscess.

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II. METHODS

A. Brain Disease Models

Six animal subjects were beagles and their average age and weight were 36 months and 13 kg, respectively. In order to investigate conductivity changes due to a regional brain ischemia, we adopted an ischemia model of the canine brain modified from the method by Purdy et al [9] and Garosi and McConnell [10]. Kang et al [11] reported clinical and histopathological findings of our canine model of ischemic stroke. After we performed an *in vivo* MREIT experiment of a normal animal, we induced a regional ischemia by occluding the left middle cerebral artery. Two days after the embolization, we conducted another *in vivo* experiment using the same animal. Brain ischemia studies were conducted using three dogs.

Brain abscess was induced in other three dogs by a direct inoculation method. The organism used to produce the abscess was Staphylococcus pseudintermedius from the cultured blood sample of the dog with endocarditis [12]. The bacteria were cultured in tryptic soy broth (BD, USA) for 12 hours. The dog was anesthetized and fixed to a standard stereotactic apparatus. The shaved scalp was surgically prepared. A single burr hole was made and 300 micro-liter of a bacterial suspension (approximately 108-109 colony forming unit) was injected into a brain tissue. The wound was flushed with a saline and hemostasis was established with a bone wax to prevent epidural hematoma formation. The skin incision was closed in layers

B. Animal Preparation for Imaging

We injected 0.1 mg/kg of atrophine sulfate to prevent dribbling during experiments. Ten minutes later, we anesthetized the dog with intramuscular injection of 0.2 ml/kg Tiletamine and Zolazepam (Zoletil 50, Virbac, France). Twenty minutes later, we clipped hair at four locations on the head where we attached four carbon-hydrogel electrodes (HUREV Co. Ltd., Korea) (Fig. 1). The size of each electrode

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was 80×80×5.76 mm^3. With four electrodes attached, we positioned the dog inside the bore of our 3 T MRI scanner (Magnum3, Medinus, Korea) (Fig. 1). The experimental protocol was approved by the Institutional Animal Care and Use Committee (IACUC) of Konkuk University, Seoul, Korea.

Inside the shield room, we intubated the dog using an endotracheal tube of 8.5 mm diameter and began the general anesthesia using a veterinary anesthesia machine system (VME, MATRX, USA). We used 2% isoflurane mixed with oxygen at 800 ml/min flow rate. Ventilation was machine-controlled by using a ventilator (M-2002, Hallowell EMC, USA) with the respiration rate of 15 bpm and tidal volume of 200 ml. Vital signs including ECG, respiration and body temperature were monitored by using a vital sign monitor (VSM7-B, MATRX, USA).

Figure 1. Experimental setup for canine head imaging using four carbon-hydrogel electrodes.

C. *Imaging Experiment*

Using a custom-designed MREIT current source, we injected 5 mA currents with positive and negative polarities as the first currents $I_1^{\pm}$ between the horizontal pair of electrodes. After acquiring the first data set with $I_1^{\pm}$ in 8 axial slices, the second injection currents $I_2^{\pm}$ with the same amplitude and width were injected through the vertical pair of electrodes. We used the multi-echo ICNE (injection current nonlinear encoding) pulse sequence. The imaging parameters were as follows: TR/TE = 1000/30 ms, number of echoes = 3, FOV = 180×180 mm^2, matrix size = 128×128, slice thickness = 4 mm, number of slices = 8, NEX = 12 and total imaging time = 100 min.

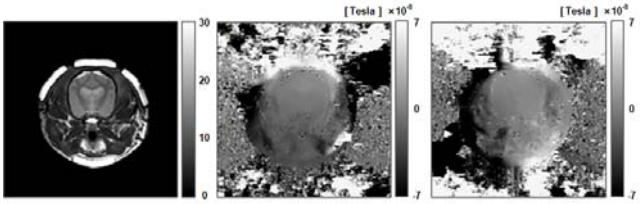
D. *Conductivity Image Reconstruction*

We used CoReHA (conductivity reconstructor using harmonic algorithms), which is an integrated software package for MREIT [13]. It provides GUI-based functions for all data processing routines needed to produce conductivity images from measured k-space data sets. We used the single-step harmonic Bz algorithm implemented in CoReHA for multi-slice conductivity image reconstructions [14]. All conductivity images presented in this paper should be interpreted as scaled conductivity images providing only contrast information.

III. RESULTS

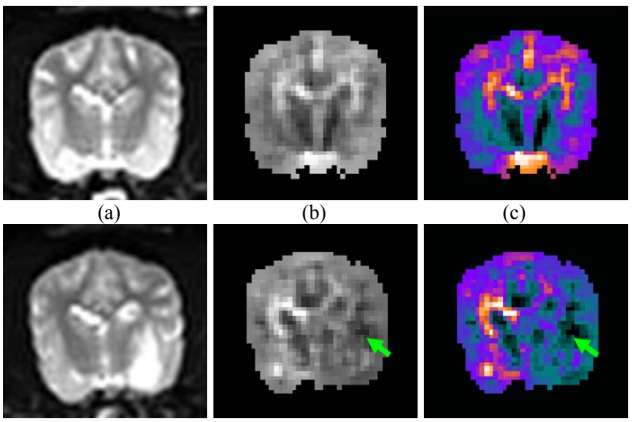
A. *Canine Brain Ischemia Model*

Fig. 2 shows MR magnitude and magnetic flux density images from a dog for the horizontal and vertical injection currents, respectively. Fig. 3(a), (b), and (c) show T2 weighted MR, conductivity, and color-coded conductivity images of the normal canine brain, respectively. Conductivity images distinguish white and gray matters and limbic areas with the pixel size of 1.4 mm. Fig. 3(d), (e), and (f) show corresponding images of the same canine brain after inducing a regional ischemia. Conductivity images show a significantly decreased contrast in the right temporal lobe, which is not apparent before the surgery. We summarized conductivity changes related with the regional ischemia in table 1. Fig. 4 shows the case of the second dog. In this case, conductivity images show a significantly decreased contrast in the left temporal lobe where a regional ischemia was induced. We expect that cell swelling due to the ischemia resulted in a reduced conductivity.



(a) (b) (c)

Figure 2. Typical *in vivo* MREIT images: (a) MR magnitude image of a canine head, (b) and (c) are magnetic flux density images of the head for the horizontal and vertical injection currents, respectively.



(a) (b) (c)

(d) (e) (f)

Figure 3. (a), (b), and (c) are T2 weighted MR, reconstructed conductivity, and color-coded images of the first normal canine brain, respectively. (d), (e), and (f) are corresponding images of the same canine brain after inducing a regional ischemia. The arrow in the right temporal lobe indicates a significantly decreased conductivity contrast.

TABLE I. RELATIVE CONDUCTIVITY CONTRAST RATIO (RCCR) OF *IN VIVO* DISEASE MODEL CANINE BRAIN.

Disease model		rCCR*	
		Before surgery	**After surgery**
Ischemia model	Canine 1	0.5 %	-0.6 %
	Canine 2	0.4 %	-0.8 %
	Canine 3	-0.2 %	-1.7 %
Abscess model	Canine 4	0.5 %	2.5%
	Canine 5	0.4 %	1.4 %
	Canine 6	0.6 %	4.7 %

* $rCCR = \left(\frac{\sigma_{abnoraml} - \sigma_{normal}}{\sigma_{normal}} \right) \times 100(\%)$, we introduce the rCCR between two different regions as quantitative criteria to compare conductivity images.

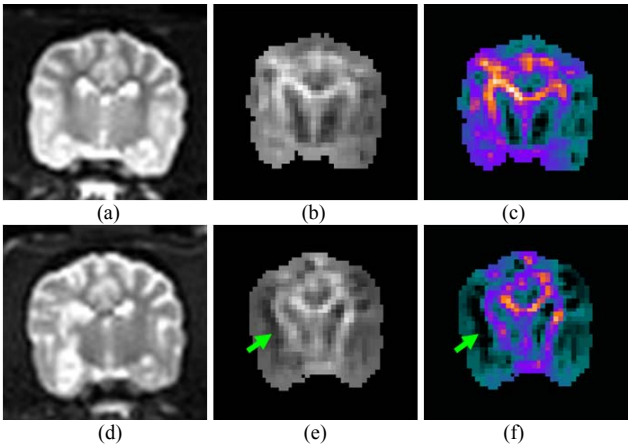


Figure 4. (a), (b), and (c) are T2 weighted MR, reconstructed conductivity, and color-coded images of the second normal canine brain, respectively. (d), (e), and (f) are corresponding images of the same canine brain after inducing a regional ischemia. The arrow in the left temporal lobe indicates a significantly decreased conductivity contrast.

B. Canine Brain Abscess Model

Fig. 5(a), (b), and (c) are T2 weighted MR, conductivity, and color-coded conductivity images of a normal canine brain, respectively. Fig. 5(d), (e), and (f) show corresponding images of the same canine brain with brain abscess. Conductivity images show a significantly increased contrast in the left frontal lobe, which is not apparent in the normal brain. Fig. 6 shows the case of other dog showing similar conductivity images in the left frontal lobe. We summarize the conductivity changes related with brain abscess in table 1. The relative conductivity contrast ratio (%, rCCR) of the abscess region is significantly higher than that of the normal region. The rCCR value between normal and abscess regions reflects the inflammatory cell infiltration, edema, hemorrhage and necrosis inside the abscess region.

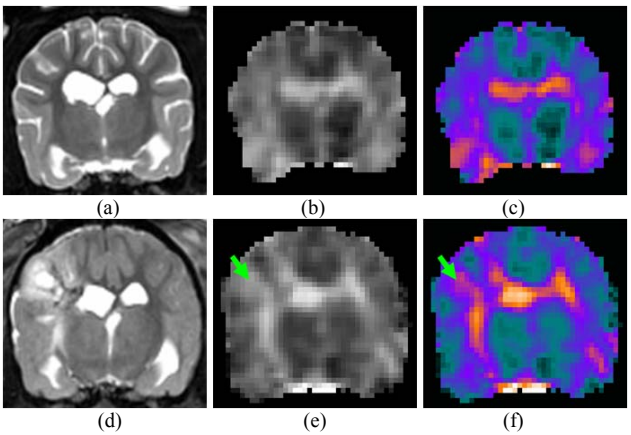


Figure 5. (a), (b), and (c) are T2 weighted MR, reconstructed conductivity, and color-coded images of the first normal canine brain before induction of brain abscess. (d), (e), and (f) are corresponding images of the same canine brain 12 hours after induction of abscess. The conductivity image shows a significantly increased contrast in the left frontal lobe (arrow), which is not apparent in before an induction of abscess.

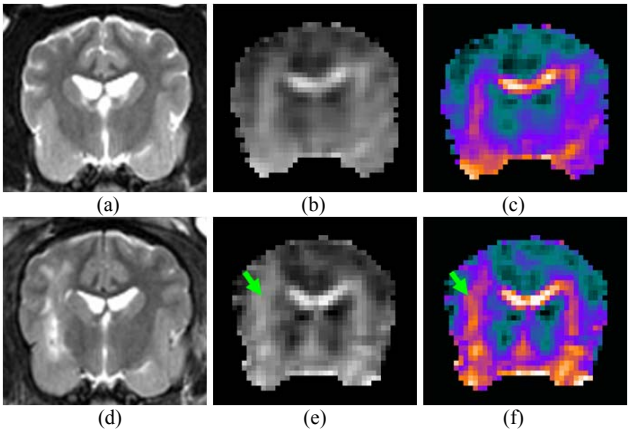


Figure 6. (a), (b), and (c) are T2 weighted MR, reconstructed conductivity, and color-coded images of the second normal canine brain before induction of brain abscess. (d), (e), and (f) are corresponding images of the same canine brain 12 hours after induction of abscess. The conductivity image shows a significantly increased contrast in the left frontal lobe (arrow).

IV. Discussion and Conclusion

MREIT has rapidly progressed in its theory, algorithm and experimental technique and now reached the stage of *in vivo* animal and human experiments. Recent animal MREIT studies showed a good conductivity contrast not only inside the brain but also in other body parts such as the abdomen, pelvis, knee and leg [6-8]. To support its clinical significance, we should demonstrate that the conductivity image provides meaningful diagnostic information that is not available from other imaging modalities. This requires accumulated experience and knowledge on how to interpret a conductivity image in relation with anatomy and pathology of a specific organ.

In this study, we performed *in vivo* disease model animal experiments to validate the MREIT technique in terms of its capability to produce a conductivity contrast corresponding to brain ischemia and abscess. Though reconstructed conductivity images in this paper do not provide absolute conductivity values, they show unique contrast information between normal and abnormal tissues compared with conventional MR image technique. We expect that this kind of *in vivo* animal imaging will provide additional diagnostic information.

Adopting most of recent technical advancements in MREIT, we could perform *in vivo* animal imaging experiments using 5 mA injection currents. For the head imaging, it would be desirable to further reduce the current amplitude to avoid any side effects such as nerve stimulation. Since the image quality depends on the SNR of measured magnetic flux density images. In order to reduce the scan time and current amplitude while keeping the image quality, we are developing fast pulse sequences for MREIT. We propose similar imaging experiments using a latest clinical MRI scanner with multiple receive channels. Adopting a parallel imaging method using a set of carefully designed RF coils will improve the measurement sensitivity.

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REFERENCES

[1] G. C. Scott, M. L. G. Joy, R. L. Armstrong, R. M. Henkelman, "Measurement of nonuniform current density by magnetic resonance", IEEE Trans. Med. Imag., vol. 10, pp. 362-374, 1991.

[2] E. J. Woo, S. Y. Lee, C. W. Mun, "Impedance tomography using internal current density distribution measured by nuclear magnetic resonance", SPIE, vol. 2299, pp. 377-385, 1994.

[3] O. Birgul, Y. Z. Ider, "Electrical impedance tomography using the magnetic field generated by injected currents", Proc. 18th Ann. Int. Conf. IEEE EMBS, pp. 784-785, 1996.

[4] O. Kwon, E. J. Woo, J. R. Yoon, J. K. Seo, "Magnetic resonance electrical impedance tomography (MREIT): simulation study of J-substitution algorithm", IEEE Trans. Biomed. Eng., vol. 49, pp. 160-167, 2002.

[5] E. J. Woo, J. K. Seo, "Magnetic resonance electrical impedance tomography (MREIT) for high-resolution conductivity imaging", Physiol. Meas., vol. 29, pp. R1-26, 2008.

[6] H. J. Kim, B. I. Lee, Y. Cho, Y. T. Kim, B. T. Kang, H. M. Park, S. Y. Lee, J. K. Seo, E. J. Woo, "Conductivity imaging of canine brain using a 3 T MREIT system: postmortem experiments", Physiol. Meas., vol. 28, pp. 1341-1353, 2007.

[7] H. J. Kim, T. I. Oh, Y. T. Kim, B. I. Lee, E. J. Woo, J. K. Seo, S. Y. Lee, O. Kwon, C. Park, B. T. Kang, H. M. Park, "In vivo electrical conductivity imaging of a canine brain using a 3T MREIT system", Physiol. Meas., vol. 29, pp. 1145-1155, 2008.

[8] H. J. Kim, Y. T. Kim, A. S. Minhas, W. C. Jeong, E. J. Woo, J. K. Seo, O. J. Kwon, "*In vivo* high-resolution conductivity imaging of the human leg using MREIT: the first human experiment", IEEE Trans. Med. Imag., vol. 28, pp. 1681-1687, 2009.

[9] P. D. Purdy, M. D. Devous Sr, C. L. White 3rd, H. H. Batjer, D. S. Samson, K. Brewer, K. Hodges, "Reversible middle cerebral artery embolization in dogs without intracranial surgery", Stroke, vol. 20, pp. 1368-13, 1989.

[10] L. S. Garosi, J. F. McConnell, "Ischemic stroke in dogs and humans: a comparative review", J Small. Anim. Pract., vol. 46, pp. 521-529, 2005.

[11] B. T. Kang, J. H. Lee, D. I. Jung, C. Park, S. H. Gu, H. W. Jeon, D. P. Jang, C. Y. Lim, F. S. Quan, T. B. Kim, Z. H. Cho, E. J. Woo, H. M. Park, "Canine model of ischemic stroke with permanent middle cerebral artery occlusion: clinical and histopathological findings", J Vet. Sci., vol. 8, pp. 369-376, 2007.

[12] D. R. Enzmann, R. R. Britt, W. G. Obana, J. Stuart, K. Murphy-Irwin, "Experimental *Staphylococcus aureus* brain abscess", Am J Neuroradiol., vol. 7, pp. 396-402, 1986.

[13] K. Jeon, H. J. Kim, C. O. Lee, E. J. Woo, J. K. Seo, "CoReHA: conductivity reconstructor using harmonic algorithms for magnetic resonance electrical impedance tomography (MREIT)", J. Biomed. Eng. Res., vol. 30, pp. 279-287, 2009.

[14] J. K. Seo, S. W. Kim, S. Kim, J. J. Liu, E. J. Woo, K. Jeon, C. O. Lee, "Local harmonic Bz algorithm with domain decomposition in MREIT: computer simulation study", IEEE Trans. Med. Imag., vol. 27, pp. 1754-1761, 2008.