Further Study of the Effects of a Time-Varying Gradient Fields on Phase Maps – Theory and Experiments

Jiasheng Su[1], Bingwen Zheng[2], Sam Fong Yau Li[2], and Shao Ying Huang[1]

[1]Singapore University of Technology and Design, Singapore, Singapore, [2]Department of Chemistry, National University of Singapore, Singapore

<u>TARGETED AUDIENCE:</u> Researchers desiring robust mapping of tissue conductivity. **PURPOSE:** Obtaining the conductivities of human tissues, σ, *in vivo* and non-invasively is important to various biomedical applications. Recently, it was reported that the retrieval of σ can be achieved through eddy currents induced by pulsed field gradients [1, 2]. In [1, 2], eddy currents caused by the time-varying gradient field has been researched to find the relationship between phase changes in the phase map and conductivity. In [3], we proposed a quasistatic electromagnetic (EM) model to study the relation among encoding gradient pulses, the induced eddy currents, and the resultant phase difference that was used for the retrieval of σ in [1]. The significant role of the discharging of accumulated charges when gradient field is constant is identified. In this abstract, the EM model is optimized. The optimized model is further applied to study the relationship of the gradient pulses, the following RF pulse, and the resultant phase difference. Another crucial discharging process to generate phase difference is identified. This discharging process offset the phase difference generated by that when the encoding gradient field is constant. It is terminated when an RF pulse is applied. This process is critical for obtaining meaningful phase maps for the retrievals of σ. Both theoretical and experimental results are presented. **METHODS:** Fig. 1 shows the sequence with time-varying encoding gradient pulses. The duration for the field-increase, constant-field, and field-decrease phases are t_1, t_2, and t_3, respectively. The duration between the instant when the gradient goes back to zero and that an RF pulse is applied is denoted as time delay (*TD*). The sequence used to retrieve σ in [1] is that when *TD* = 0. Eq. (1) – (6) show an optimized quasistatic EM model for the gradient fields, eddy currents, and change of magnetic fields (that leads to change of phase).

$$\vec{B}_g = \frac{\mu}{4\pi}\oint_C \frac{\vec{J}_g \times (\vec{r}-\vec{r}\,')}{\left|\vec{r}-\vec{r}\,'\right|^3} d\ell \qquad (1)$$

$$\vec{E} = \frac{\varepsilon_0}{\varepsilon}\frac{\mu}{4\pi}\int_{V'} \frac{\partial \vec{J}_g}{\partial t} \Big/ \left|\vec{r}-\vec{r}\,'\right| \qquad (2)$$

$$\vec{J}_e = \sigma\vec{E} \qquad (3)$$

$$\vec{J} = \vec{J}_e - \sigma\vec{E}_\rho \qquad (4)$$

$$\vec{E}_\rho = \frac{1}{4\pi\varepsilon}\int_{V'} \frac{\vec{r}-\vec{r}\,'}{\left|\vec{r}-\vec{r}\,'\right|^3}\rho dv' \qquad (5)$$

$$\nabla\cdot\vec{J} = \frac{\partial\rho}{\partial t} \qquad (6)$$

Eq. (1) is Biot-Savart law where $\vec{J}_g$ is the current in the gradient coil and $\vec{B}_g$ is the gradient field, Eq. (2) calculates the induced electric field (e-field) in the medium with a dielectric constant of ε. Eddie current $\vec{J}_e$ and the total current $\vec{J}$ can be obtained using (3) and (4), respectively. In (4), $\vec{E}_\rho$ is the e-field induced mainly by the accumulated charges that opposes $\vec{E}$. $\vec{E}_\rho$ and $\vec{J}$ can be calculated based on (5) and (6), respectively. Based on the model, both a time-varying magnetic field and the discharging afterwards when the field stops varying contribute to phase changes. The discharging starts when the gradient field stops increasing and becomes a constant. It is stopped when the gradient field starts decreasing and the medium is exposed to an induced e-field. When the gradient field goes back to zero and there is no external e-field, the discharging process starts again. It is in an opposite direction to that of the discharging when the gradient field is a constant during t_2. The reason is that these two processes are caused by the two induced e-fields in opposite directions during t_1 and t_3. The phase difference generated in *TD* offsets that generated in the t_2-duration. This discharging during *TD* is terminated when an RF pulse is applied where a strong external e-field is imposed. **RESULTS & DISCUSSIONS:** Fig. 2 (a) shows the induced current when the field has an ascending rate of 50 T/m/s within 2ms and an estimated one in another 2ms when the field is a constant. Fig. 2 (b) shows the induced current when the field decreases at a rate of 50 T/m/s within 2ms and an estimated one in another 2ms when there is no field. From *t* = 2ms to 4ms, the eddy current decreases due to the discharge process and an exponential model is used. As can be seen in Fig. 2, the induced currents are in opposite directions when the field increases and decreases during t_1 and t_3, respectively. The charges are accumulated in opposite directions, thus the induced currents by discharging during t_2 and *TD* go in opposite directions. A cylindrical phantom with 1% gel and 0.5% NaCl as shown in Fig. 3 was scanned in an Agilent preclinical MRI 7T scanner. Fig. 4 shows the measured phase differences by applying the [1 1 1] and [-1 -1 -1] sequences in Fig. 1 [1]. The ascending and descending rates are both to be 50 T/m/s, $t_1 = t_3$ = 2ms. In Case 1-3, t_2 = 0ms, 100ms, and 200ms, *TD* = 0ms where an RF pulse is applied immediately when the gradient field goes to zero. As can be seen in Fig. 4, at t_2 = 0ms, the phase difference introduced by an ascending field is compensated by that generated by a descending field. The figure also shows when t_2 increases, phase difference increases because the discharging process starts. The observation agrees with the conclusion in [3]. Case 3-8 correspond to *TD* = 0ms, 50ms, 100ms, 200ms, 400ms, and 600ms, respectively. In these cases, t_2 = 200ms. In Fig. 4, it is observed that the phase difference introduced by the discharging during t_2 = 200ms (when the gradient field is a constant) is offset by the discharging after the gradient field goes back to zero. It is completely cancelled out when t_2 = *TD* = 200ms. The phase change starts to saturate at *TD* = 400ms. **CONCLUSIONS:** A critical discharging process is identified when the gradient field goes to zero before an RF pulse is applied (where there are no external e-fields). It offsets the effects of the other discharging process when the gradient field is a constant that generates phase differences for retrieving conductivity. The time delay between the encoding gradient pulse and the following RF pulse plays a crucial role in generating the phase changes in the phase map that are used for conductivity retrievals.

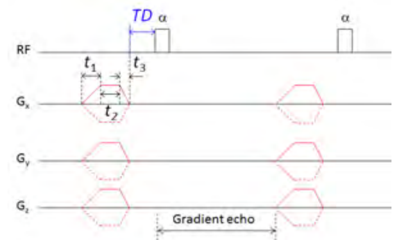
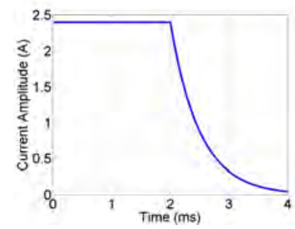


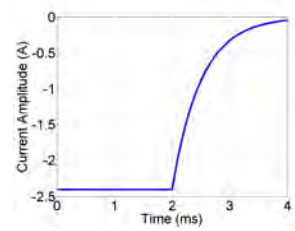
Fig.1 The time-varying encoding gradient fields [1]

Table I

	t_1	t_2	t_3	*TD*
Case 1	2ms	0ms	2ms	0ms
Case 2	2ms	100ms	2ms	0ms
Case 3	2ms	200ms	2ms	0ms
Case 4	2ms	200ms	2ms	50ms
Case 5	2ms	200ms	2ms	100ms
Case 6	2ms	200ms	2ms	200ms
Case 7	2ms	200ms	2ms	400ms
Case 8	2ms	200ms	2ms	600ms



(a) During t_1 and t_2



(b) During t_3 and *TD*

Fig. 2 The induced current versus time

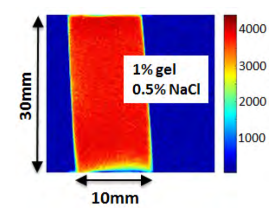


Fig.3 The model of experiment

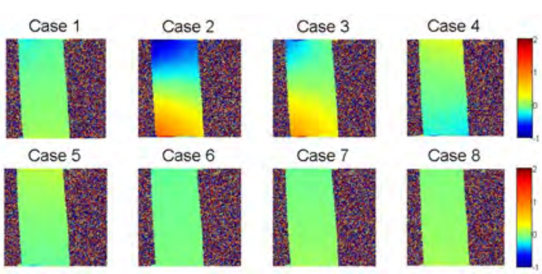


Fig.4 Measured phase by applying sequence in Fig. 1

REFERENCES: 1. Chun L. et al. ISMRM 2014 0638. 2. Stefano M et al, ISMRM 2014 0639. 3. J. Su et al, 3rd Int. Workshop on MRI PC & QSM 2014