An Algorithm for Applying Multiple Currents Using Voltage Sources in Electrical Impedance Tomography

Myoung Hwan Choi, Tzu-Jen Kao, David Isaacson, Gary J. Saulnier, and Jonathan C. Newell

Abstract: A method to produce a desired current pattern in a multiple-source EIT system using voltage sources is presented. Application of current patterns to a body is known to be superior to the application of voltage patterns in terms of high spatial frequency noise suppression, resulting in high accuracy in conductivity and permittivity images. Since current sources are difficult and expensive to build, the use of voltage sources to apply the current pattern is desirable. An iterative algorithm presented in this paper generates the necessary voltage pattern that will produce the desired current pattern. The convergence of the algorithm is shown under the condition that the estimation error of the linear mapping matrix from voltage to current is small. Simulation results are presented to illustrate the convergence of the output current.

Keywords: Current sources, electrical impedance tomography, multiple currents, voltage sources.

1. INTRODUCTION

Electrical impedance tomography (EIT) is a technique for determining the electrical conductivity and permittivity distributions in the interior of a body from measurements made on its surface. Typically, currents are applied through electrodes placed on the body's surface and the resulting voltages are measured. Alternately, voltages can be applied and the resulting currents are measured. Recent reports on a number of EIT systems can be found in [3-7]. In Adaptive Current Tomography (ACT) systems, currents are applied to all the electrodes, and voltages are measured simultaneously. Multiple patterns of currents are applied to produce the current and voltage data necessary for an image. A typical system description can be found in [10]. If the body being imaged is circular or cylindrical, and measurements are performed using a single ring of electrodes around the body, the most common current patterns used are spatial sinusoids of various frequencies. In this paper, we focus on a current delivery system for an ACT-type EIT system that uses multiple voltage sources.

The image reconstruction problem in EIT is ill-posed, and large changes in the conductivity and permittivity in the interior produce only small changes in the currents or voltages at the surface. As a result, measurement precision in EIT systems is of critical importance if accurate reconstruction of the conductivity and permittivity is to be achieved. It is known that when current is applied and the resulting voltages are measured, the errors in the measured data are reduced as the spatial frequency increases, proportionally to the inverse of the spatial frequency [1]. The scheme of applying currents and measuring the voltages is less sensitive to errors than the scheme of applying voltages and measuring currents. The use of current sources gives better immunity to the unknown electrode contact impedances and the maximum current delivered to each electrode is easily limited for patient safety [9].

In practice, however, current sources are difficult as well as expensive to build [2]. Building a high precision current source is a technologically challenging task. The current source must have output impedance sufficiently large compared to the load at the operating signal frequency to ensure that the desired current is applied for various loads. It is even more difficult to design such a current source if the

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system is to operate over a wide range of signal frequencies, as is required for EIT spectroscopy [7]. The implementation of high-precision current sources has generally required the use of calibration and trimming circuits to adjust output impedance up to sufficient levels, yielding relatively complex circuits.

A voltage source, however, is easier and less expensive to build and operate than a current source. It requires less circuit board space, and can be more easily and quickly calibrated. EIT systems applying voltage patterns using voltage sources have been implemented, though these systems suffer from increased sensitivity to the high spatial frequency noise. Ideally, one would like the simplicity of voltage sources with the noise advantages of current pattern application. A portable EIT device powered by a battery would require such a technique.

Here we present an approach for applying the desired current pattern using voltage sources in an ACT-type EIT system. The amplitudes and phases of ac voltage sources need to be adjusted in a way that they produce the desired current pattern. An iterative algorithm was reported in [8] where the individual voltage sources are adjusted using a concept of an effective load. The current was shown to converge to the desired value in a majority of the experiments, though this is not guaranteed. Inversion of the admittance matrix was used in [9] to generate current patterns from voltage sources. When the admittance matrix can be computed exactly, this method results in the desired current values. Estimation error in the admittance matrix, however, can result in errors in the current values. In EIT systems where the measurement precision is of critical importance, we require the current errors to be as small as possible.

This paper presents a computation algorithm that generates the voltages in a more systematic way, and the condition for the current convergence is given in an explicit form. This paper is organized as follows: In Section 2, the problem formulation of the current generation using voltage sources is presented, and an iterative algorithm is derived. In Section 3, simulation results of the proposed iterative algorithm are presented, followed by conclusions in Section 4.

2. PROBLEM FORMULATION AND ITERATIVE ALGORITHM

Examples of applying multiple currents to a human body and a two dimensional human thorax phantom can be found in [5] and [11] respectively. In the two-dimensional human thorax phantom in [11], a cylindrical tank contains models of lung and heart made of agar, and it is filled with saline solution. Total of 32 electrodes are placed around the inner circumference of the tank, and used to flow 28KHz ac current, and measure the resulting voltages. A system block diagram for driving the electrodes with currents and measuring voltage data is reported in [10], and more details of the instrumentation is described in [3].

In this work, we want to apply voltage to the electrodes and to measure currents. Let $I=(I_1, I_2,\cdots,I_L)^T$ denote an Lx1 electrode current vector where I_n is ac current on electrode *n*, and *L* is the number of electrodes. Similarly let $V=(V_1,V_2, \cdots,V_L)^T$ denote an Lx1 electrode voltage vector. The mapping from the applied electrode voltage *V* to the measured electrode current *I* can be represented using a constant LxL admittance matrix *A* so that $I=AV$ [9], provided that the change with time in the electrical conductivity and permittivity of human body under examination is assumed to be negligible or the change is slow compared to the fast sampling time of the measurement. The elements of *I*, *V* and *A* are in general complex numbers.

The goal is to compute voltage pattern V^d that will generate the desired electrode current pattern I^d. The matrix *A* can be estimated from the measurement data, but the exact value of *A* can not be determined. The estimate of *A*, denoted as $\hat{A}$, can be obtained experimentally by applying a set of independent current patterns and measuring the corresponding output voltages. Then, $\hat{A}$ can be used to compute V^d. However, $\hat{A}$ would contain errors due to modeling errors in the geometry of the electrodes in addition to the measurement errors. In this paper, an iterative algorithm for computing the voltage $V^d=(V_1^d, V_2^d,\cdots,V_L^d)^T$ is presented that will produce a desired current pattern I^d with high precision in the presence

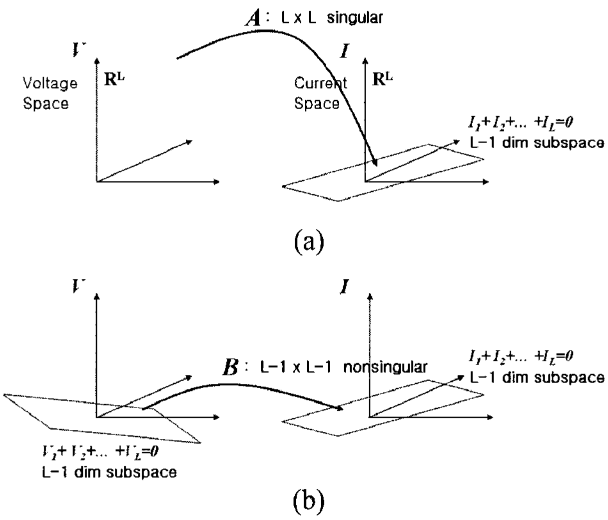

Fig. 1. (a) Linear mapping from the voltage space to current space is singular. (b) A nonsingular mapping from a voltage subspace to the current subspace.

of the estimation errors in $\hat{A}$.

When the voltage pattern is applied and a current pattern is produced, the sum of the electrode currents through the body is zero. Because of this constraint on the electrode current values, the dimension of the current vector space that can be generated by applying voltages is L-1, while the dimension of the voltage space is L as shown in Fig. 1(a). The linear mapping A from the voltage space to the current subspace given by $I=AV$ is a singular mapping.

The linear mapping from voltage space to the current space can be formulated as a nonsingular mapping if the sum of the applied electrode voltages is constrained to be zero. Then, the mapping from L-1 dimensional voltage subspace to L-1 dimensional current subspace can be represented by an (L-1)x(L-1) nonsingular matrix B as shown in Fig. 1(b). Let us choose an orthonormal basis set $\{T^n\}_{n=1}^{L-1}$ for the voltage and current subspaces, where $T^n = \left[T_1^n \; T_2^n \cdots T_L^n\right]^T$. In the notation T_i^j, the subscript i denotes the electrode number, and superscript j denotes the vector number. Since $\{T^n\}_{n=1}^{L-1}$ are the basis vectors for the current and voltage vector spaces where the sum of the vector elements are zero, we know $\sum_{n=1}^{L} T_n^k = 0$ for all k. Since they are basis vectors, we know $<T^k, T^x> = \delta_{k,x}$, where $<T^k, T^x>$ is the inner product of T^k with T^x. The current and voltage vectors can be represented using coordinate vectors with respect to the basis vector set.

$$I = \sum_{n=1}^{L-1} i_n T^n, \text{ where } i_n = <I, T^n>,$$
$$V = \sum_{n=1}^{L-1} v_n T^n, \text{ where } v_n = <V, T^n>.$$

In the above expression, i_n and v_n are the n-th coordinates of the current I and voltage V with respect to the basis T^n. Let us apply the voltage T^k to the electrodes and measure the electrode current I^k, k=1,2...L-1. Then, $I^k = AT^k$. The relationship from the applied voltage V to the measured current I is

$$I = AV,$$
$$\sum_{m=1}^{L-1} i_m T^m = \sum_{n=1}^{L-1} v_n A T^n,$$
$$\sum_{m=1}^{L-1} i_m T^m = \sum_{n=1}^{L-1} v_n I^n.$$

Taking the inner product of both sides with T^u, $u = 1, 2, \cdots, L-1$,

$$i_u = \sum_{n=1}^{L-1} <T^u, I^n> v_n, \quad u = 1, 2, \cdots, L-1.$$

Let $i = [i_1 \; i_2 \cdots i \; L-1]^T$, $v = [v_1 \; v_2 \cdots v_{L-1}]^T$. Then, we can write

$$i = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_{L-1} \end{bmatrix} = \begin{bmatrix} <T^1, I^1> & <T^1, I^2> & \cdots & <T^1, I^{L-1}> \\ <T^2, I^1> & <T^2, I^2> & \cdots & <T^2, I^{L-1}> \\ \vdots & \vdots & \vdots & \vdots \\ <T^{L-1}, I^1> & <T^{L-1}, I^2> & \cdots & <T^{L-1}, I^{L-1}> \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_{L-1} \end{bmatrix}.$$

Then, the linear mapping from the coordinate vector v to the coordinate vector i is nonsingular, and described by

$$i = Bv, \tag{1}$$

where B is a (L-1)x(L-1) nonsingular matrix.

$$B = \begin{bmatrix} <T^1, I^1> & <T^1, I^2> & \cdots & <T^1, I^{L-1}> \\ <T^2, I^1> & <T^2, I^2> & \cdots & <T^2, I^{L-1}> \\ \vdots & \vdots & \vdots & \vdots \\ <T^{L-1}, I^1> & <T^{L-1}, I^2> & \cdots & <T^{L-1}, I^{L-1}> \end{bmatrix}. \tag{2}$$

We apply voltage T^k to the electrodes and measure I^k, k=1, ... L-1, and compute the estimate of B denoted as $\hat{B}$ using (2). The coordinate vector i^d of the desired current $I^d = (I_1^d, I_2^d, \cdots, I_L^d)^T$ is computed by

$$i^d = \begin{bmatrix} i_1^d \\ i_2^d \\ \vdots \\ i_{L-1}^d \end{bmatrix} = \begin{bmatrix} <I^d, T^1> \\ <I^d, T^2> \\ \vdots \\ <I^d, T^{L-1}> \end{bmatrix}.$$

Now, we can use the nonsingular linear mapping $i=Bv$ to compute the voltage that will produce a desired current pattern, and the procedure is summarized below.

Proposition 1: Given a desired current I^d and error tolerance ε, we can compute the voltage V^* that will produce the current I^* such that $\| e \| = \| I^d - I^* \| < \varepsilon$ as below, provided that the estimation error of $\hat{B}$ is small such that $\|Q\|<1$ where $Q=(I-B\hat{B}^{-1})$.

1. Compute $\hat{B}$ and i^d.
2. Let $e_0=i^d$, $v^0=V^0=0$, $k=0$
3. Let k=k+1. Compute $v^k=v^{k-1}+\hat{B}^{-1}e_{k-1}$.

   Apply $V^k=\sum_{n=1}^{L-1}v_n^k T^n$ to the electrodes, and measure I^k.

   Compute $i^k=\begin{bmatrix} i_1^k \\ i_2^k \\ \vdots \\ i_{L-1}^k \end{bmatrix}=\begin{bmatrix} <I^k,T^1> \\ <I^k,T^2> \\ \vdots \\ <I^k,T^{L-1}> \end{bmatrix}$.

   Compute $e_k=i^d-i^k$.
4. If $\|e_k\|<\varepsilon$ then let $V^*=V^k$ and stop. Else go to 3.

Claim 1: The k-th error in Proposition 1 is $e_k=Q^k i^d$ where $Q=(I-B\hat{B}^{-1})$. Furthermore, if $\|Q\|<1$, then $\|e_k\|<\|e_{k-1}\|$ and $\|e_k\|<\|Q\|^k\|e_0\|$ holds for $k\geq 1$.

Proof: If the Claim 1 were true in the (k-1)-th step, i.e., $e_{k-1}=Q^{k-1}i^d=(I-B\hat{B}^{-1})^{k-1}i^d$. Then, $v^k=v^{k-1}+\hat{B}^{-1}e_{k-1}=v^{k-1}+\hat{B}^{-1}(I-B\hat{B}^{-1})^{k-1}i^d$. Also, $i^k=Bv^k=Bv^{k-1}+B\hat{B}^{-1}(I-B\hat{B}^{-1})^{k-1}i^d=i^{k-1}+B\hat{B}^{-1}(I-B\hat{B}^{-1})^{k-1}i^d$.

The error at the k-th step is

$$\begin{aligned} e_k &= i^d-i^k=i^d-i^{k-1}-B\hat{B}^{-1}(I-B\hat{B}^{-1})^{k-1}i^d \\ &= e_{k-1}-B\hat{B}^{-1}(I-B\hat{B}^{-1})^{k-1}i^d \\ &= (I-B\hat{B}^{-1})(I-B\hat{B}^{-1})^{k-1}i^d \\ &= (I-B\hat{B}^{-1})^k i^d=Q^k i^d. \end{aligned}$$

The assumption is true for k=1, i.e., $e_1=i^d-i^1=i^d-B\hat{B}^{-1}i^d=(I-B\hat{B}^{-1})i^d=Qi^d$. Thus, the error expression is proved. Next, the convergence of the error is shown when $\|Q\|<1$.

$$\|e_k\|=\|Q^k i^d\|=\|Qe_{k-1}\|\leq\|Q\|\|e_{k-1}\|<\|e_{k-1}\|$$

Also, we can show

$$\|e_k\|\leq\|Q\|\|e_{k-1}\|\leq\|Q\|^2\|e_{k-2}\|\leq\cdots\leq\|Q\|^k\|e_0\|.$$

Thus, the error satisfies $\|e_k\|\leq\|Q\|^k\|e_0\|$ and is monotonically decreasing as k increases if the convergence condition $\|Q\|<1$ is satisfied. □

Claim 1 states that if the estimation error of $\hat{B}$ is small such that $\|I-B\hat{B}^{-1}\|<1$, then the generated current approaches the desired current asymptotically.

3. SIMULATION RESULTS

The test data were obtained from measurements of a 2-D circular homogeneous saline phantom tank using the EIT instrument ACT 3 [5].

The basis vectors of the current and the voltage subspace used for this circular 2D geometry are

$$T_l^n=\begin{cases} M_n\cos n\theta_l, & n=1,2,\cdots,L/2,\ l=1,2,\cdots,L \\ M_n\sin(n-L/2)\theta_l, & n=L/2+1,\cdots,L-1,\ l=1,2,\cdots,L, \end{cases}$$

where θ_l is the angle of the electrode l with respect to the center of the disk. M_n is chosen to normalize T^n. A total of 31 voltages resulting from 31 linearly independent current patterns were measured, and converted to their coordinate vectors. The matrix B was computed from (1) and regarded as the true mapping.

In order to simulate the estimation error, random multiplicative errors and additive errors were added to each element of B to make up $\hat{B}$. In order to introduce 1% multiplicative error, a random number x was generated with uniform distribution between -0.01 and +0.01 for each element of B, and the element was multiplied by $(1+x)$. For additive error, xB_{max} was added to each element of B, where B_{max} is the element of B with maximum absolute value. In order to simulate the current measurement noise, a set of random numbers was generated with uniform distribution between -1 and 1, the magnitudes of the noise were adjusted so that the SNR is 105 dB as reported in [3], and were added to the current measurements.

The desired current value used in the simulation was $I_k^d=0.2\cos\theta_k+j0.1\sin\theta_k$ (mA) for the k-th electrode. The real part of I^d is one of the actual current patterns used in the ACT 3 measurements. The imaginary part was added for test purpose. Fig. 2 shows the convergence of the current to the desired value as the iteration count increases. Five lines represent the results with different multiplicative and additive errors. For example, error 1.0% (plotted as squares) means that the multiplicative error of 1% and additive error of 1% were introduced as the estimation error. It can be seen that when the estimation errors are 1.5%, 2.0%, and 2.5%, $\|Q\|_2$ are greater than 1, but the current still converges to the desired value. The convergence condition $\|Q\|_2<1$ is a sufficient

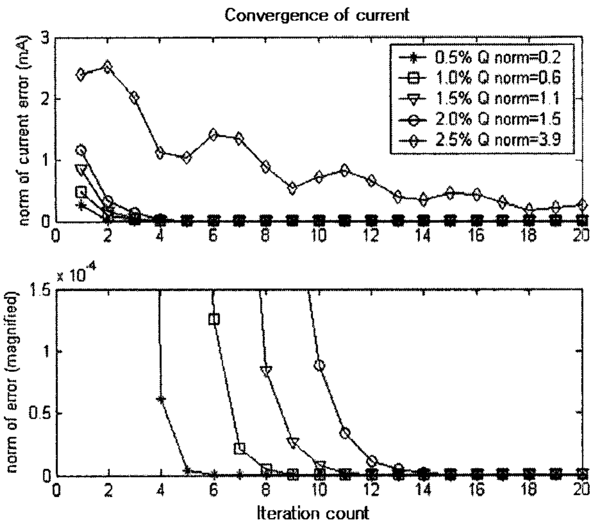

Fig. 2. Convergence of the current output when no current measurement noise is present.

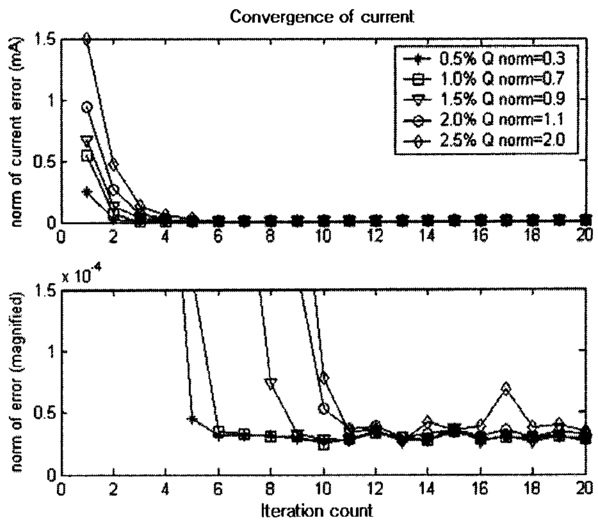

Fig. 4. Convergence of the current output when current measurement noise is present.

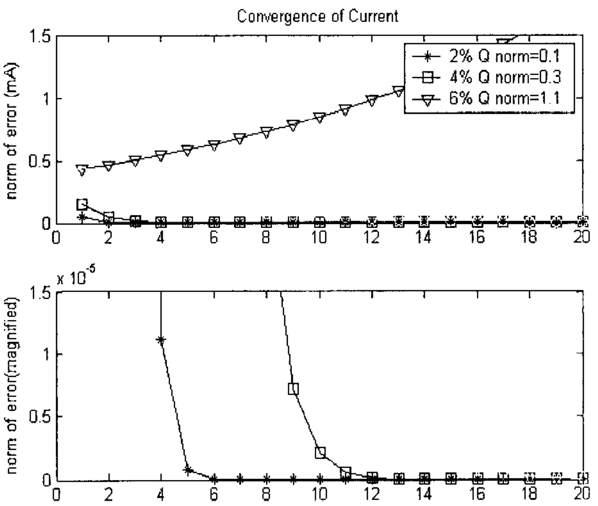

Fig. 3. Example showing the divergence of the current when no current measurement noise is present.

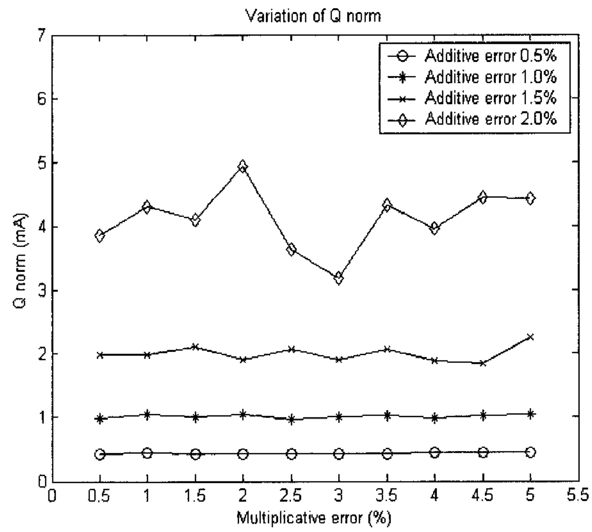

Fig. 5. Variation of $\|Q\|_2$ with multiplicative and additive errors.

condition. Even when the condition is not satisfied, the current convergence is still possible, though not guaranteed. Results in Fig. 2 shows the cases where $\|Q\|_2>1$ and the current error goes to zero. An example of current divergence is shown in Fig. 3, where the estimation error was 6% and $\|Q\|_2=1.1$. Fig. 4 shows the same simulation with current measurement noise added. The noise level corresponds to the SNR of 105dB, and this value is the measured noise level of the ACT3 machine. It is seen that the current almost converges to the desired value, but some level of error remains. The remaining error is the consequence of the current measurement noise, and the figure shows that the current error is not zero when the current measurement is corrupted by measurement noise. If $\|Q\|<1$, it is guaranteed to converge to the desired value by Claim 1. The speed of the convergence depends on the magnitude of $\|Q\|$. The next question is how realistic the condition $\|Q\|<1$ is in practice. Fig. 5 shows the behavior of $\|Q\|_2$ with the variation of multiplicative and additive errors. Multiplicative error and additive errors were varied independently, and their effect on $\|Q\|_2$ was studied. It can be seen that the current convergence condition $\|Q\|_2<1$ is satisfied when the additive error was less than 1%. In the current state of the art technology for the instrumentation of EIT hardware, the authors believe that additive error and multiplicative error in the estimation of the matrix B can be controlled to well below 1%. If the multiplicative and additive error of the current EIT instrument were less than 1%, the convergence condition of the example used in this work could be satisfied.

4. CONCLUSIONS

We have shown that if the matrix of the linear mapping from the voltage coordinate vector to the current coordinate vector can be estimated within a small error bound, the current output produced by applying the voltage can be made to approach the desired current value. In the absence of the measurement error, it was shown that when the convergence condition was satisfied, the current output approached the desired value asymptotically. In the presence of measurement error, the current approaches the neighborhood of the desired value. The convergence of the current in the presence of the measurement noise remains to be studied in the future research works.

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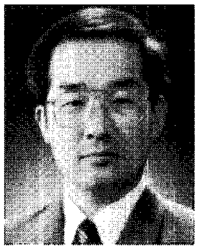

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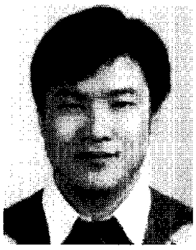

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