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Distinguishability of inhomogeneities using planar electrode arrays and different patterns of applied excitation

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Abstract

Electrical impedance tomography (EIT) is a non-invasive technique used to image the electrical conductivity and permittivity within a body from measurements taken on the body surface. Four methods are being investigated for breast cancer diagnosis by EIT today: Single voltage source, single current source and multiple current sources with a fixed pre-determined 'canonical' pattern of currents and an adaptively determined 'optimal' pattern of currents. To determine which of these four methods might yield the best distinguishability using planar electrode arrays for breast cancer detection, we placed electrode arrays on a saline tank and used each excitation pattern to detect a conducting target placed at the centre of a flat electrode array in two geometries: mammography geometry and single probe geometry. The result was that the multiple current sources method had higher distinguishability than either the SCS or the SVS method. In both these electrode geometries, the optimal current pattern had higher distinguishability than the other patterns at all distances.

Keywords: distinguishability, optimal current pattern, impedance imaging, electrical impedance tomography (EIT)

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Four methods are being investigated for breast cancer diagnosis by electrical impedance tomography (EIT). One may be termed the single current source (SCS) method, used by Korjenevsky *et al* [1]. It applies a current to each electrode sequentially, and measures the resulting voltage on all other electrodes. Another may be termed the single voltage source (SVS) method used by the T-SCAN system [2], which applies a constant voltage to a flat array of electrodes on the body relative to a single electrode held in the hand and measures the resulting currents at each of several electrodes. The Adaptive Current Tomography 3 system

(ACT 3) [3] has an independent current source and voltage meter for each electrode. This multiple current source (MCS) system offers a chance to study the effect of the current pattern. We applied the same current to each electrode simultaneously and measured the resulting voltages as the third method. For the fourth method, we applied the current pattern given by the adaptive algorithm [4], which is optimized to distinguish the difference between the saline tank with and without a target.

The purpose of the present study is to compare the distinguishability obtainable by these four methods. The results are interpreted in terms of the distinguishability defined by Isaacson [4]. This term has several possible definitions. We have used two of these, the norm distinguishability and power distinguishability. They both quantitatively assess the effect of placing a target in the tank on the data obtained from each method.

Distinguishability is a term introduced by Isaacson in 1987 [4] to provide a quantitative measure of the ability of impedance imaging systems to distinguish two conditions from each other by electrical impedance measurements. It is a characteristic of the measurement system, and can be calculated from the data obtained from a system without the need to reconstruct an image from that data. If a measurement system has a known, fixed level of measurement precision, then an object may be said to be distinguished from a homogeneous background, for example, if its distinguishability is greater than the measurement precision.

In this paper, we report the results of experiments conducted in water tanks with copper targets near planar electrode arrays attached to the ends of the tank. Having a distinguishability higher than a noise or error threshold is a necessary but not sufficient condition for making a useful image. In general, higher distinguishability implies a larger signal for a reconstruction algorithm to work with. The goal of this paper is to compare the distinguishability of impedance imaging datasets. These results may help guide the choice among different measurement schemes, numbers of electrodes and achievable levels of noise in designing an impedance imaging system.

2. Methods

2.1. Geometry

We studied the effect of four different excitation patterns in two geometries: mammography geometry (figure 1(a)) and single probe geometry (figure 1(b)). We placed electrode arrays in a saline (370 mS m^{-1}) tank and used various excitation patterns to study a conductive target placed at different distances in front of the central electrode. The size of the target was $2.4 \times 2.4 \times 2.4$ cm^3 positioned by a Stereotaxic Instrument, which has 0.1 mm precision. In mammography geometry, we applied positive excitation patterns to each electrode of a square array at one end of the tank and negative excitation patterns to a similar array at the other end of the tank; the sum of the currents was zero. In single probe geometry, we applied patterns to each electrode of a square array at one end of the tank and an electrode at the other end was connected to ground.

To compare the distinguishability between different electrode sizes and the number of electrodes, we built a square array of 25 stainless steel electrodes of the same area and same net area of electrodes as the nine-electrode array. Table 1 shows the electrode size.

2.2. Excitation

To determine the best pattern for detecting an inhomogeneity in a homogeneous tank, distinguishabilities of several excitation patterns were compared. These excitation patterns are:

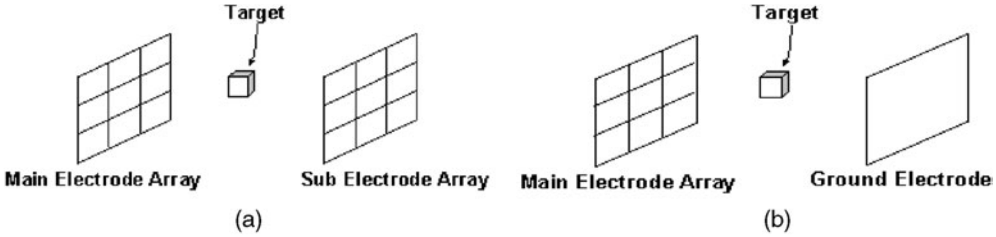

Figure 1. (a) Mammography geometry 3 × 3 × 2 (as shown). (b) Single probe geometry 3 × 3 (as shown) or 5 × 5.

Table 1. Sizes of electrodes and the gaps between electrodes.

Array	Size of each electrode (mm)	Total area of all electrodes (mm^2)	Gap (mm)	Width of the entire array (mm)
3 × 3	24.7 × 24.7	5477	3	$24.7 \times 3 + 3 \times 2 = 80$
5 × 5	14.8 × 14.8	5476	1.5	$14.8 \times 5 + 1.5 \times 4 = 80$

Table 2. Excitation patterns I_{opt}.

Channel	Iteration 1 to 9								
1	1.0000	0.1949	0.1581	0.1524	0.1512	0.1509	0.1508	0.1508	0.1508
2	1.0000	0.3246	0.2807	0.2757	0.2749	0.2747	0.2747	0.2747	0.2747
3	1.0000	0.1712	0.1463	0.1453	0.1454	0.1455	0.1455	0.1456	0.1456
4	1.0000	0.3401	0.2897	0.2813	0.2794	0.2790	0.2788	0.2788	0.2788
5	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
6	1.0000	0.3064	0.2842	0.2859	0.2869	0.2872	0.2873	0.2873	0.2873
7	1.0000	0.1806	0.1412	0.1365	0.1357	0.1356	0.1355	0.1355	0.1355
8	1.0000	0.2950	0.2625	0.2608	0.2609	0.2610	0.2610	0.2610	0.2610
9	1.0000	0.1700	0.1456	0.1457	0.1463	0.1465	0.1465	0.1465	0.1465

- I_{single}: a current was applied from each electrode to ground sequentially, and the resulting voltage was measured on all electrodes [1]. This pattern uses a SCS.
- V_{const}: the currents required to produce a uniform voltage on all electrodes were found experimentally, iteratively, and then measured [2]. This is called the SVS method.
- I_{const}: the same value of current was applied to each electrode simultaneously and the resulting voltage was measured on each electrode. This is called the multiple current source (MCS) method.
- I_{opt}: the current pattern given by the adaptive algorithm [4], which is optimized to distinguish the difference between the saline tank with and without a target, was obtained and applied. (Table 2 shows the optimal current pattern for the 3 × 3 array using the adaptive algorithm and iterations starting with I_{const} then converge to I_{opt} after eight iterations.)

The measurement time for each pattern was 4.6 ms to apply the current and measure the voltages on all electrodes. The precision of the voltmeters is nominally16 bits, so the quantization noise level is about 0.012 mV in ACT 3 [3]. For example, to apply I_{single} to the 3 × 3 array requires 4.6 × 9 ms, but it only takes 4.6 ms for the other three methods.

3. Distinguishability

3.1. Norm distinguishability

Isaacson [4] has developed criteria to distinguish between two conductivities σ^0 and σ^1 inside the body. For the following analysis, let $V(\sigma^0, j)$ be the measured voltage when current density j is applied to the homogeneous background with no target, and $V(\sigma^1, j)$ be the measured voltage on the tank with a target. We say that two different conductivities are distinguishable, in the mean square sense, by a measurement with precision ε_i if and only if

$$\|V(\sigma^0, j) - V(\sigma^1, j)\| > \varepsilon_i \tag{1}$$

for the current density j for which $\|j\| = 1$ where norm $j = \|j\| = \left(\int j^2\,\mathrm{d}x\right)^{1/2}$.

In [4], $\delta_l(\sigma_1, \sigma_0, j)$, the norm distinguishability in the mean square sense, was defined by

$$\delta_l(\sigma^1, \sigma^0, j) = \frac{\|V(\sigma^0, j) - V(\sigma^1, j)\|}{\|j\|}. \tag{2}$$

For this paper, we define the norm distinguishability in the mean square sense to be

$$\sqrt{\frac{\sum_{l=1}^{L} |V_l(\sigma^0, j) - V_l(\sigma^1, j)|^2}{\sum_{l=1}^{L} |I_l|^2}} \tag{3}$$

where the currents, I_l, are simultaneously applied to the electrodes l, l =1, 2, 3, ..., L, and use it to compare discrete current and voltage measurements. It is proportional to a discrete approximation to δ_l.

The I_{single} excitation pattern actually consists of nine current patterns for the 3 × 3 electrode array and 25 for the 5 × 5 electrode array, because it applies a current to each electrode sequentially. We computed the average value ($I_{\text{single-avg}}$) and maximum value ($I_{\text{single-max}}$) in order to compare the norm distinguishability with others. If a pattern $I^{(1)}$ has a higher norm distinguishability than another pattern $I^{(2)}$, this means that when $\sum_{l=1}^{L}\left(I_l^{(1)}\right)^2 = \sum_{l=1}^{L}\left(I_l^{(2)}\right)^2$ then $\sum_{l=1}^{L}\left(\delta V_l^{(1)}\right)^2 > \sum_{l=1}^{L}\left(\delta V_l^{(2)}\right)^2$, thus the target can be more easily detected by pattern $I^{(1)}$ than $I^{(2)}$.

3.2. Power distinguishability

Equation (2) gives the distinguishability for the current source system, but does not take the power into account. To compare the distinguishability between a current source system and a voltage source system, we compare the relative power. An inhomogeneity is detectable if the change in power is greater than the measurement precision ε_p with which the system can measure power. That is

$$|P(\sigma^0) - P(\sigma^1)| > \varepsilon_p \tag{4}$$

and the relative power change is defined as

$$\delta_p(\sigma^1, \sigma^0) = \frac{|P(\sigma^0) - P(\sigma^1)|}{|P(\sigma^0)|} \tag{5}$$

where power P is proportional to the real part of $\sum_{l=1}^{L} IV$. Here the sum is over all the electrodes on which current may be applied or voltages may be measured. If a pattern has a higher power distinguishability, it means that the pattern can create a larger power difference between the homogeneous and inhomogeneous states. Thus the target will be easier to detect.

The norm and power distinguishabilities used in this paper do not depend on the magnitude of the total currents used and only depend on the shape of the patterns used. Thus one could

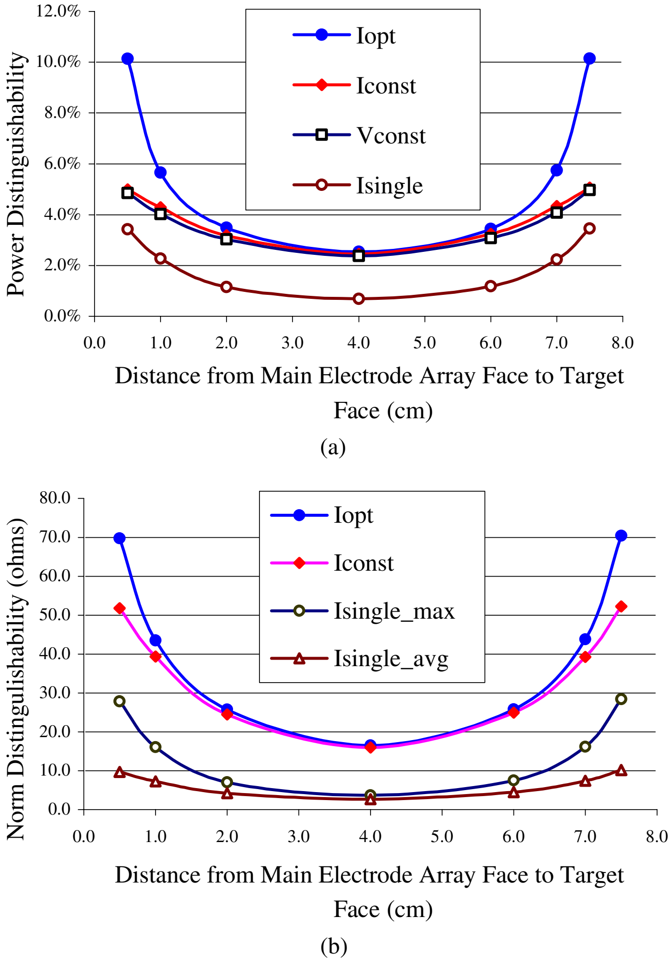

Figure 2. (a) Power distinguishability for four different excitation patterns in mammography geometry. (b) Norm distinguishability for different current patterns in mammography geometry.

use large total currents or small total currents as long as they had the same ‘shaped pattern’ and should get the same ‘distinguishability’.

4. Results

4.1. Mammography geometry

We applied the four different excitation patterns to the 3 × 3 × 2 array and placed a cubical conductive target at various distances from the array, then measured the resulting voltage or current and computed the distinguishabilities (figures 2(a) and (b)). Distinguishability decreased for each excitation pattern as the target was moved away from the main electrode array and reached its lowest value when target was in the middle between the two electrode arrays. Distinguishability rose again when the target moved closer to the sub electrode array. At all distances, the optimal current (I_{opt}) to distinguish the target had higher distinguishability than the other patterns. The constant current pattern (I_{const}) for the inhomogeneous tank had a

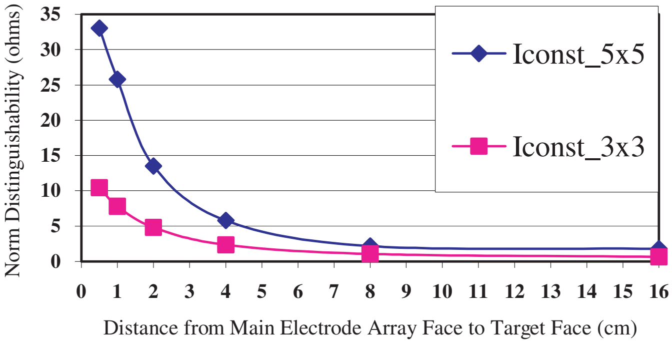

Figure 3. Norm distinguishability of 3 × 3 and 5 × 5 arrays using a unit current 0.1 mA applied to every electrode.

low distinguishability if the target was near the electrodes, but it remained high as the target moved farther away, and converged to the optimal pattern (I_{opt}) at large distances.

The total applied current for each excitation pattern could be different but the norm distinguishability is independent of $\sum_{l=1}^{L}(I_l)^2$, because δV_l is proportion to applied current I_l. This means we could use same amount of total applied current and get the same distinguishability result.

4.2. Comparison of 5 × 5 and 3 × 3 planar array

To compare the distinguishability of 3 × 3 and 5 × 5 electrode arrays, we used the single probe geometry and applied a unit current 0.1 mA to every electrode and measured the resulting voltage. Norm distinguishability of the 5 × 5 electrode array was greater than for the 3 × 3 electrode array (figure 3). In other words, a large number of smaller electrodes have higher distinguishability than an electrode array with fewer, larger individual electrodes with the same overall array area (table 1, figure 3). This result gives evidence to support the use of a large number of smaller electrodes, when designing an EIT system. Therefore, in what follows for the single probe geometry, we report results from the 5 × 5 electrode array.

In this experiment, the total currents used for 3 × 3 and 5 × 5 were in the ratio of 9:25. However, the quantity measured and plotted in figure 3—norm distinguishability—is the same for all magnitudes of total current. It is chosen specifically to be a measure of the shape of the pattern of currents ability to distinguish an inhomogeneity and is independent of the magnitude of the total current used. It has units of resistance (Ohms). This follows from the definition and the fact that the voltages are proportional to the magnitude of the currents used, so the magnitude of the total current divides out of the ratio in the same way that a single voltage measured across a single resistor when divided by the single current applied to that resistor is independent of the magnitude of the current applied.

4.3. Single probe geometry

Distinguishability decreased for each current pattern as the cubical conductive target was moved away from the 5 × 5 electrode array. At all distances, the optimal current (I_{opt}) to distinguish the target had higher distinguishability than the other patterns. The constant current pattern (I_{const}) for the inhomogeneous tank had a relatively low distinguishability if the target was near the electrodes, but this decreased slowly as the target moved farther away, and converged to the optimal pattern (I_{opt}) at large distances (figure 4).

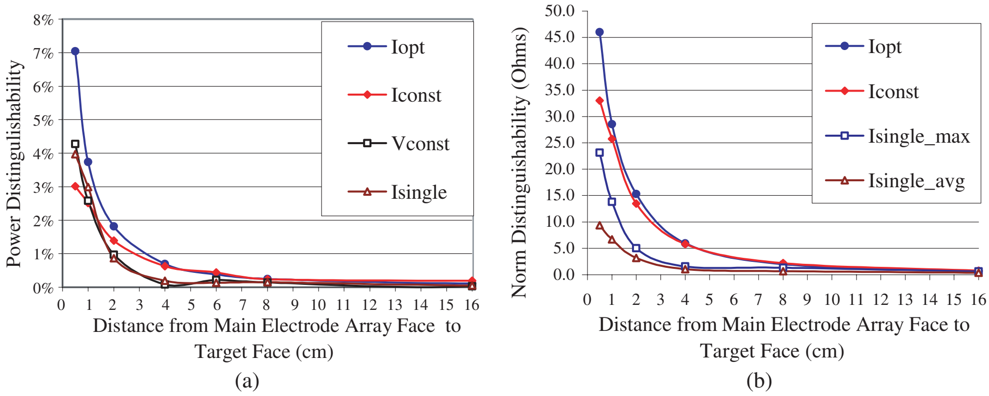

Figure 4. (a) Power distinguishability for four different excitation patterns in single probe geometry. (b) Norm distinguishability for different current patterns in single probe geometry.

We note that the power distinguishabilities of V_{const} and I_{single} reach the noise floor when the target moved further than 4 cm from the electrodes, but for I_{opt} and I_{const}, distinguishability was higher when the target was at 4 cm than when it was at 8 cm. (Figure 5 shows the resulting voltage difference as the distance between the target and the electrode array changed from 0.5 cm to 8 cm.) After 8 cm, the distinguishability of all cases fell to the noise level, which means that this target may not be distinguished from the homogeneous tank. Therefore, with the precision of this system, optimal current patterns (I_{opt}) allowed one to detect this target almost twice as far from the electrodes as was possible with the V_{const} and I_{single} patterns (figure 6).

5. Discussion

Using a planar electrode array to detect a target in a homogeneous tank, distinguishability decreased for each excitation pattern as the target was moved away from an electrode array. Increasing the number of individual electrodes, while keeping the same total electrode area, increased distinguishability.

For both geometries, the optimal current pattern (I_{opt}) had a higher distinguishability than other patterns at all distances and the maximum detected distance of optimal current pattern (I_{opt}) is almost twice as large as for the other patterns.

The constant current (I_{const}) had a relatively low distinguishability if the target was near the electrodes, but it converged to the I_{opt} patterns at a further distance. I_{const} has higher norm distinguishability than the single current pattern (I_{single}), demonstrating that MCSs have better distinguishability than an SCS. The relatively high distinguishability of the constant current patterns suggests that they may be more desirable than the optimal current patterns in situations where the time needed to calculate the optimal patterns might not be available. Either constant or canonical patterns may offer near-optimal distinguishability in many cases.

This study suggests four ways to increase the distinguishability of an EIT system using planar arrays:

a. For the probe design, in constant electrode array area, we should increase the number of electrodes.
b. Increase the precision of the system.
c. Use multiple current sources.
d. Use optimal current patterns.

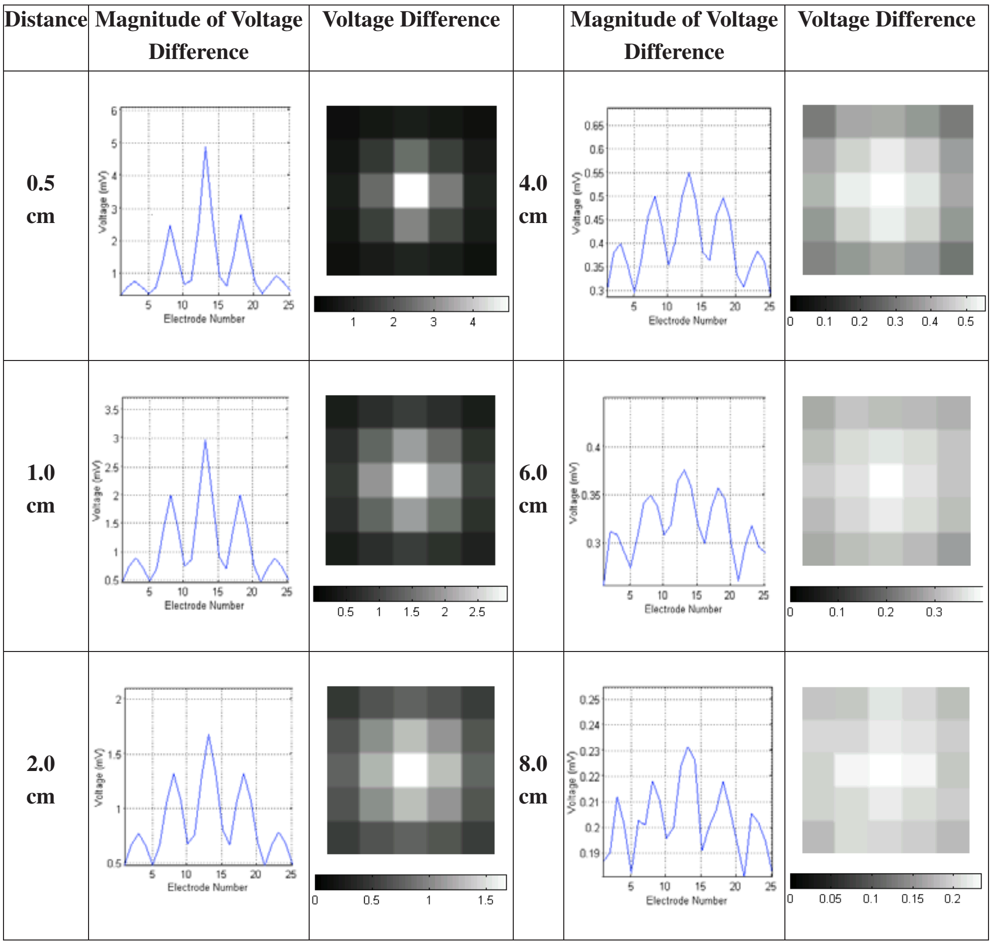

Figure 5. Resulting voltage for single probe geometry using I_{opt} (max: 0.1 mA).

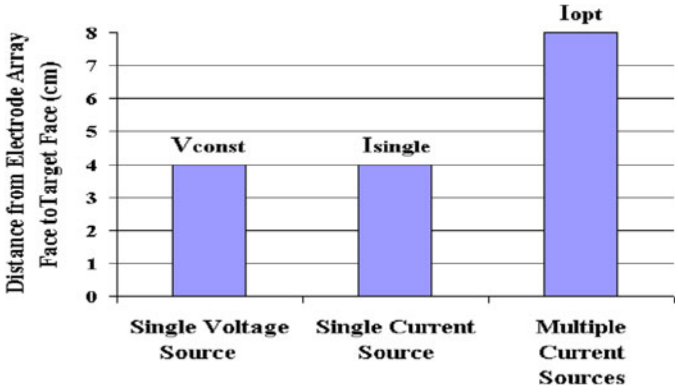

Figure 6. The maximum detected distance for different excitation patterns.

The ability of a system to detect breast cancer can only be determined by clinical trials that find the sensitivity, specificity, safety, and comfort on a statistically significant patient population. Until that is done one can have any opinion one wants as to the 'optimal' method of screening for breast cancer by EIT. It is hoped that this study has made clear to the reader some of the experimental reasons why we are building and testing MCS systems that can produce 'optimal current patterns' for the purpose of improving the detection of breast tumours smaller than those that can be detected by existing systems.

Acknowledgments

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