HAEMATOMA DETECTION USING EIT in a SHEEP MODEL

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Abstract

Performance evaluation of a portable digital electrical impedance tomography system to detect haematomas using phantom and sheep models is presented. Experiments have been performed using 8-electrode full array configuration. Conductivity changes were detected in phantom model while anomalies were placed at center and close to the edge of the tank. Bleeding rate was successfully monitored in sheep model while blood-like conductivity solution was injecting via the brainstem. EIT images were reconstructed sequentially for different injection volumes and the quantity index (QI) was calculated as a function of the injected solution volume. The results show a linear relationship of QI to the injected volume. Images of the sheep experiment with the simulated haematomas, blood-like conductivity gel, placed on top of the parietal lobes of the brain on the left and right sides were reconstructed and haematomas are clearly detected and localized. These experiments prove that the detection and quantification of haematomas in the brain is possible and encourage further investigation for medical applications.

Key Words

Electrical Impedance Tomography, Haematoma, Sheep Model, Assistive Medical Technology, Medical Image Processing

1. Introduction

Intracranial haematomas are pockets of blood that build-up within the cranial vault as a result of haemorrhage from a head injury. The haemorrhage is an active bleeding and the haematoma's excess blood is not reabsorbed into the body system and may also increase in size and become a serious condition. These pockets expand and increase the intracranial pressure on the brain, causing impairment of the ability of the brain to function and worsening the neurological condition of the patient. If left unchecked, the growing haematoma will cause severe and even permanent damage to the delicate tissue of the brain, the morbidity, and eventual death of the patient. The development of the haematoma from benign to symptomatic can be sudden, and a patient can change from lucid to a state of rapid neurological deterioration over a very short period of time [1].

Acute imaging of the head is the first action when a patient arrives in the emergency department on suspicion of head injury to identify the necessity of urgent (treatments) surgical intervention or stabilization to prevent further injury. The current appropriate imaging technique used in the acute phase is CT scanning. However CT scanning or MRI in the UK are not always available for 24 hours a day, and in cases of multiple traumas, it may not be possible to scan the patient until they have been adequately stabilised. The transporting requirement of ill patients and equipment compatibility restrict using this method for the acute care. These imaging techniques are not portable and suitable for continuous monitoring and involve large personnel or equipment cost [2].

There is a direct and urgent clinical need for a robust, easy to use and low-cost system which can accurately detect the presence of a haematoma in high risk patients. A device of this nature can reduce treatment delays, save on costs and waste, and most significantly, positively impact patient outcomes. It also provides a primary and possibly sole method of haematoma detection when CT scanning or MRI is unavailable or impossible. Treatment delays are mitigated by giving better and earlier information on haematomas at the triage stage. The time from injury to treatment is a key factor in patient recovery, and earlier diagnosis leads to earlier treatment.

Electrical impedance tomography (EIT) is a non-invasive, non-radiating, non-ionizing and inexpensive technique. EIT has the capability of long term monitoring and can be

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used to approximately localize the bleeding site. EIT is a medical imaging technique which reconstructs cross-sectional images of the electrical property distribution of an object within a body based on voltage measurements on its boundary. Data acquisition is performed through an array of electrodes which are attached to the surface of the body. EIT has been extensively researched in various clinical applications due to its potential to distinguish between healthy and abnormal components of an organ [3].

EIT is a relatively new medical imaging modality and present significant possibilities for medical application, including head and abdominal imaging. The aim of this paper is to evaluate the sensitivity of a digital EIT system constructed in our laboratory to detect and localize simulated haematomas in phantom and sheep models. The relationship between the injected simulated blood and the conductivity distribution in EIT images was investigated in a sheep's head.

2. Materials and Methods

2.1. System Specification and Methods

The structure of the designed EIT system based on a microcontroller is presented in Fig. 1. The system is controlled by a microcontroller connected to a PC through a serial port (RS232). A graphical user interface was developed using Visual Basic (VB). The Constant Current Source, CCS generates a constant sinusoidal current fed by a sinusoidal signal of the same frequency generated by the Direct Digital Synthesizer, DDS.

The current was injected through one pair of adjacent electrodes and the corresponding boundary potentials were measured over pairs of the remainder of the neighbouring electrodes using a multiplexer. The input pair of electrodes was switched over all adjacent pair electrodes and the measurement procedure was repeated for all possible adjacent pairs. The measurements were amplified using an Instrumentation Amplifier (IA) to produce a complete voltage data set. The performance of this system was previously evaluated using phantom experiments [4].
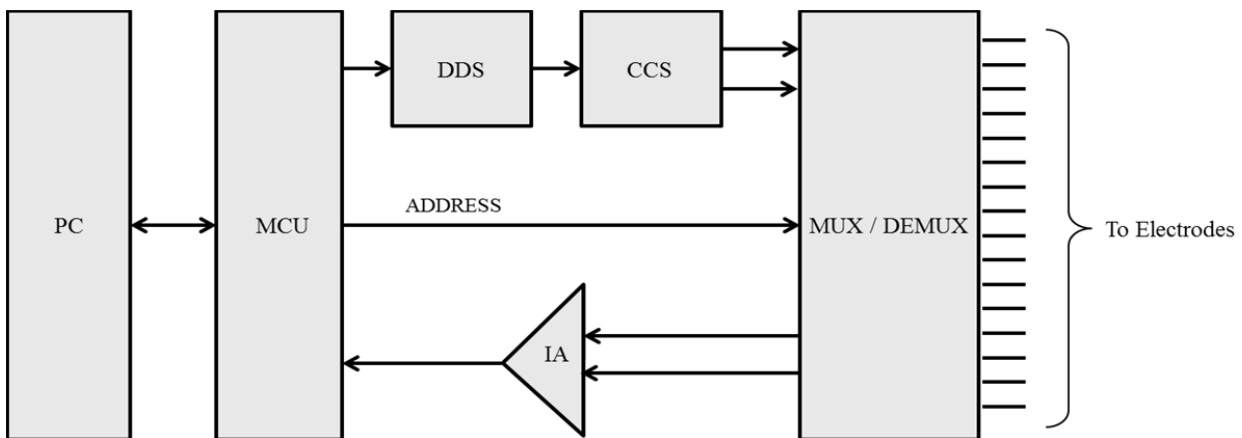

Figure 1. EIT system architecture

This multi-frequency EIT system has 16 channels and operates in the frequency range of 25 kHz to 100 kHz with the temporal resolution of 100 frames per second. For this experiment, a constant current of 1mA at a single frequency of 50 kHz and 8 electrodes were chosen.

2.2. Phantom Configuration

The EIT system is evaluated using phantom experiments in the presence of realistic noise. The phantom system consists of a shallow nylon

tank, eight electrodes, the background solution, and the simulated anomalies (cucumber segments). The tank has a depth of 80 mm and an inner diameter of 144 mm. The phantom is equipped with 8 stainless steel screws as point electrodes (dia. 10 mm) equally spaced in a ring around the tank wall. All the lead wires are of equal lengths to obtain an identical impedance path through all the electrodes in order to reduce the mismatch in electrode impedances. 0.38% saline solution with the conductivity of approximately 1 S/m is used for the background solution. Cylindrical pieces of cucumber with the conductivity of 0.05 S/m are used as anomalies. The anomalies have a diameter of approximately 40 mm and the same height as the tank

2.3.Sheep Preparation

Two fresh sheep heads were obtained from a local butcher and skinned. The locations of the 8 electrodes of the full array configuration were marked on the skull with the equal distance between electrodes. Eight 10 mm Ag/AgCl disk electrodes (Unimed Electrode Supplies Ltd) were fastened to the skull using conductive paste (Unimed Electrode Supplies Ltd).

A saline solution with the same conductivity as blood (0.67 S/m) was made with the concentration of 0.33% [weight/volume] of sodium chloride in water. In the first sheep's head the blood-equivalent saline was injected near the ventricles via the brainstem. The injections were made in increments of 0.5 ml to 9 ml using a long syringe. Blood has higher conductivity than brain tissue (0.17 S/m) thus increases in blood volume should result in increase of conductivity increment in the reconstructed images [5].

In the above experiment, blood was spread out inside the skull without any limitation because of the absence of cerebrospinal fluid and brain pressure. In order to simulate a more realistic haematoma in an accurate location, the saline solution was transformed to gel. The saline solution was stirred using a magnetic stir bar at a temperature of 70°C while agar powder (Fisher Scientific) was added to achieve the

desired gel concentration (1.7% by weight). Then the solution was poured into a tube with the diameter of 1 cm and allowed to cool at room temperature. The gel sample was removed from the tube and cut to lengths of 3 mm to use as pockets of blood. The conductivity of the gel sample was measured and found to be the same as the conductivity of the saline solution. An AC voltage was applied across the gel at a frequency of 50 kHz at room temperature using a waveform function generator connected in series with a digital multimeter to measure the AC current and AC voltage across the gel.
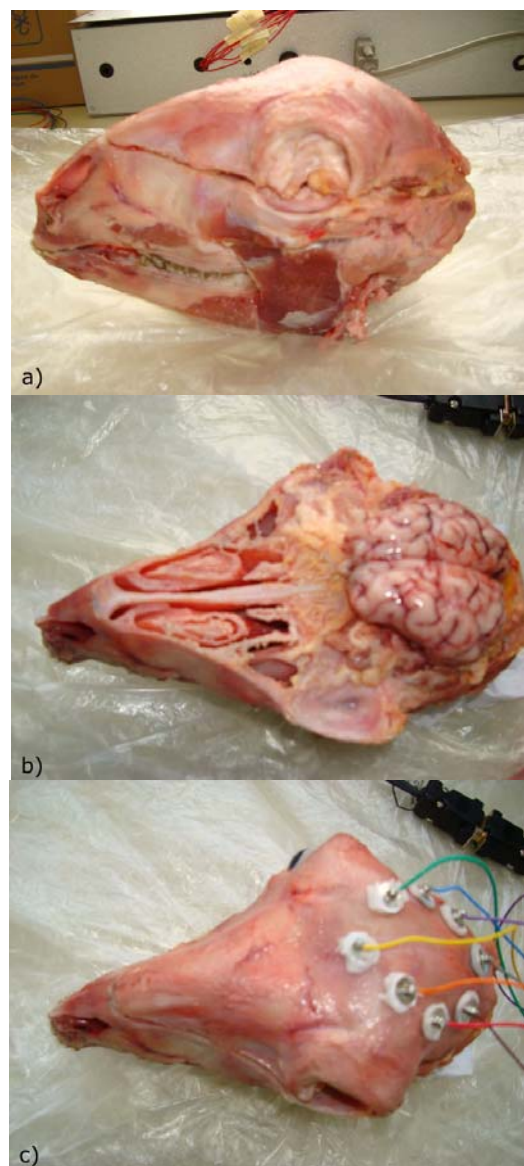

Figure 2. (a) Side view of sheep with cut skull. (b) top view with complete brain out. (c) top view with full array electrodes attached

For the second sheep's head, the skull was cut approximately in half as shown in Fig. 2 using a bone saw. The top half of the skull was carefully removed and the brain was exposed. A gel sample was placed on top of the parietal lobes at approximately the middle of the posterior quarter of the brain on the left and right sides. The top half of the skull was replaced and the measurement was performed.

2.4. Reconstruction and Processing

EIT is composed of forward problem and inverse problem. The forward problem is to predict the measured boundary electric potentials from the known applied current density and conductivity distribution. The aim of the inverse problem which is also known as image reconstruction is to estimate the conductivity distribution from a known set of boundary voltage measurements.

For the forward problem the complete electrode model was used and defined by the following equations (1-4):

$$\nabla \cdot (\sigma \nabla u) = 0 \qquad \text{on } \Omega \qquad (1)$$

$$u + z_l \sigma \frac{\partial u}{\partial n} = V_l \qquad \text{on } \varepsilon_l, l = 1,2,\dots,L \qquad (2)$$

$$\int_{\varepsilon_l} \sigma \frac{\partial u}{\partial n} ds = I_l \qquad \text{on } \varepsilon_l, l = 1,2,\dots,L \qquad (3)$$

$$\sigma \frac{\partial u}{\partial n} = 0 \qquad \text{on } \partial\Omega \backslash \{\varepsilon_1 \cup \varepsilon_2 \cup \dots, \varepsilon_L\} \qquad (4)$$

To provide the forward solution, the Finite Element Method (FEM) was used in Comsol (Comsol Multiphysics).

The images were reconstructed using the sensitivity method. The sensitivity matrix was calculated from forward solutions of a two-dimensional disk model. The model was discretized to 3032 second-order triangular finite elements. The conductivity distribution of the brain tissue is generally not known *a priori* and therefore S was calculated assuming a homogenous conductivity distribution. To determine the conductivity changes, the sensitivity matrix was inverted as equation (5):

$$\Delta\sigma \cong S^\dagger \Delta V \qquad (5)$$

where $S^\dagger$ is the Moore-Penrose pseudo inverse of S. Since the EIT inverse problem is severely ill-posed and a small amount of noise on boundary measurements, ΔV, can cause a large oscillation for the solution, $\Delta\sigma$, a regularization technique was used to reduce this effect by improving the conditioning of S. The truncated Singular Value Decomposition (TSVD) method which has previously been identified as a suitable regularization method [6] was used to regularize the inversion of the sensitivity matrix. The truncation point k, needs to be chosen carefully, less than or equal to the rank of the matrix, as it would otherwise produce inaccurate images. The truncation point was chosen on inspection of the L-curve of experimental data [7].

The quantity index (QI) is defined as an EIT image parameter that correlates with the anomaly volume. The quantity index (QI) is the integral of conductivity change multiplied by the area of the element over the image area as equation (6):

$$QI = \sum_{i=1}^{ne} \Delta\sigma_i a_i \qquad (6)$$

where, for an element (or pixel) i, $\Delta\sigma_i$ is the conductivity change reconstructed in the *i-th* element, a_i is the area of each element and ne is the total number of elements.

The position of the anomaly (x, y) can be estimated from reconstructed images using by equations (7-8):

$$x = \frac{\sum_{i=1}^{ne} \Delta\sigma_i a_i x_i}{\sum_{i=1}^{ne} \Delta\sigma_i a_i} \qquad (7)$$

$$y = \frac{\sum_{i=1}^{ne} \Delta\sigma_i a_i y_i}{\sum_{i=1}^{ne} \Delta\sigma_i a_i} \qquad (8)$$

The expression for anomaly location (x, y) is effectively the centre of the reconstructed anomaly. The values x_i and y_i are the coordinates of the centre of each element. Diametric conductivity plot (DCP) is the conductivity difference profile of the model based on the diameter passing through the reconstructed object center. It is plotted in terms of the arc-length of the diameter.

3. Results

Fig. 3 and 4 show DRP (Conductivity Difference Profile) and the reconstructed images of the phantom with single target from the potential data. The images are successfully reconstructed and the targets at different positions are clearly detected. In the images conductivity decreasing of 0.95 S/m appeared in the image in accordance with the position of the target. The single target placed at the center is illustrated in Fig. 3, and close to the edge of the tank at electrode No. 1 is shown in Fig. 4. It is observed that the reconstructed DRPs almost follow the DRP of the original object.
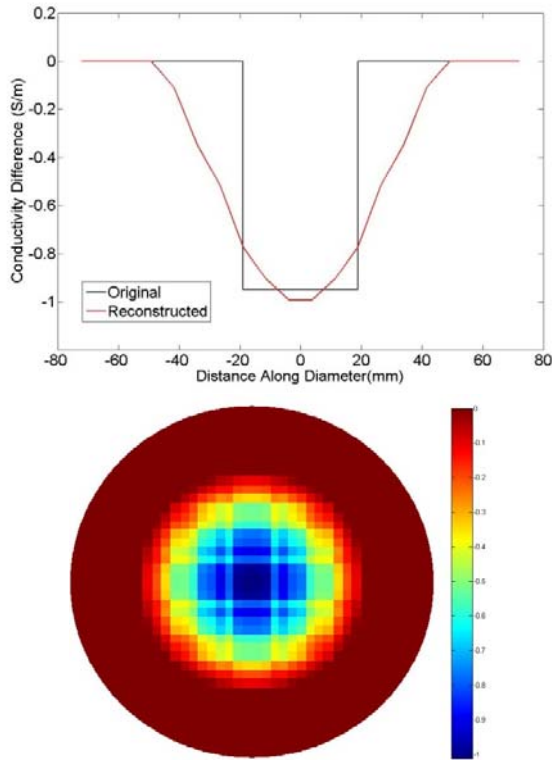
Figure 3. DRP and reconstructed image of phantom with one target at center

In the first sheep's head, where the blood-like solution was injected into the ventricles, the location of the solution was not accurately known. Therefore, the EIT images were reconstructed sequentially and the quantity index was calculated as a function of the injected solution volume as shown in Fig. 5. The plot shows the linear relationship between QI and injected volume. The calculated QI increased as more solution is injected.
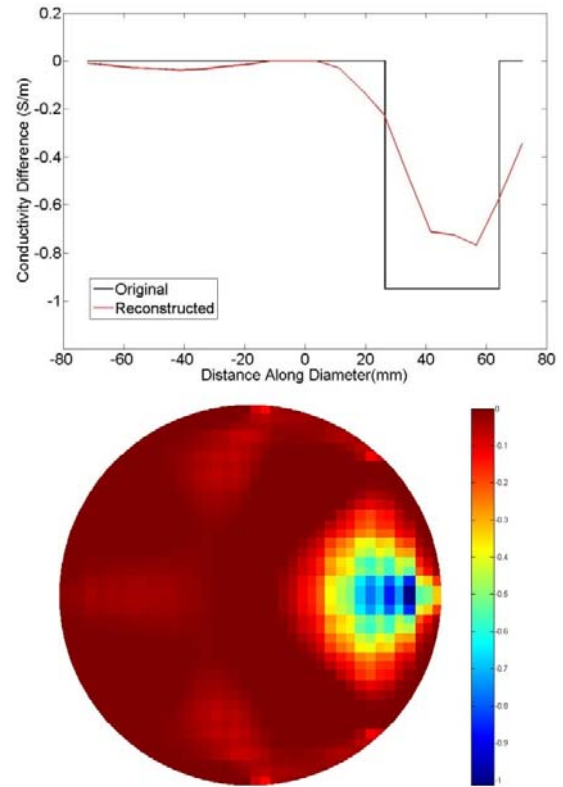
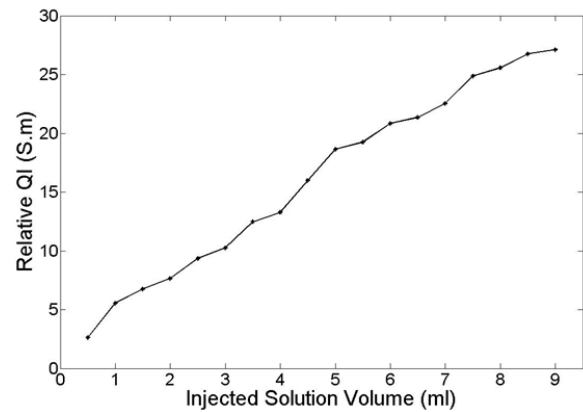Figure 4. DRP and reconstructed image of phantom with one target close to edge of the tank

Figure 5. Quantity index as a function of injected saline solution volume

In the second sheep's head, a simulated haematoma was placed at a certain position. DCP and the reconstructed image of the brain with such a haematoma placed on top of the left parietal lobe are shown in Fig. 6. It can be seen that the image is successfully reconstructed and

the haematoma is clearly detected. In the image, the red region (which represents a conductivity increase of approximately 1 S/m) appeared in the image in accordance with the position of the haematoma. It is observed that the reconstructed DCP almost follows the DCP of the original object. The center of the reconstructed anomaly on the left side was calculated as (-0.5240R, -0.4584R) where R is the radius of the imaged brain.

DCP and the reconstructed image of the brain with a haematoma placed on top of the right parietal lobe are also shown in Fig. 7. In the reconstructed image the main perturbation is produced close to the correct location with localized changes corresponding to the haematoma. The reconstruction shows the haematoma on the right side and the reconstructed DCP almost follows the DCP of the original object. The center of the reconstructed anomaly on the right side was calculated as (0.4043R, -0.5282R).
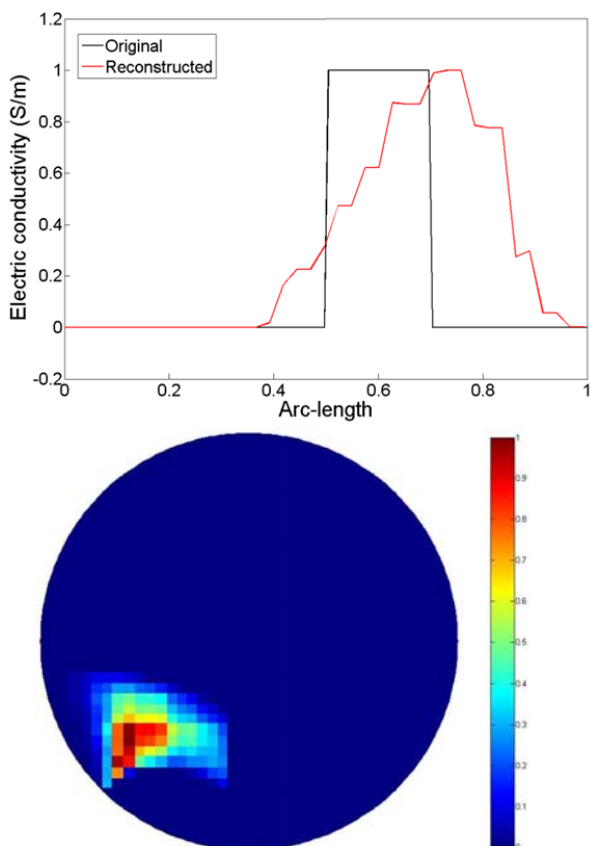

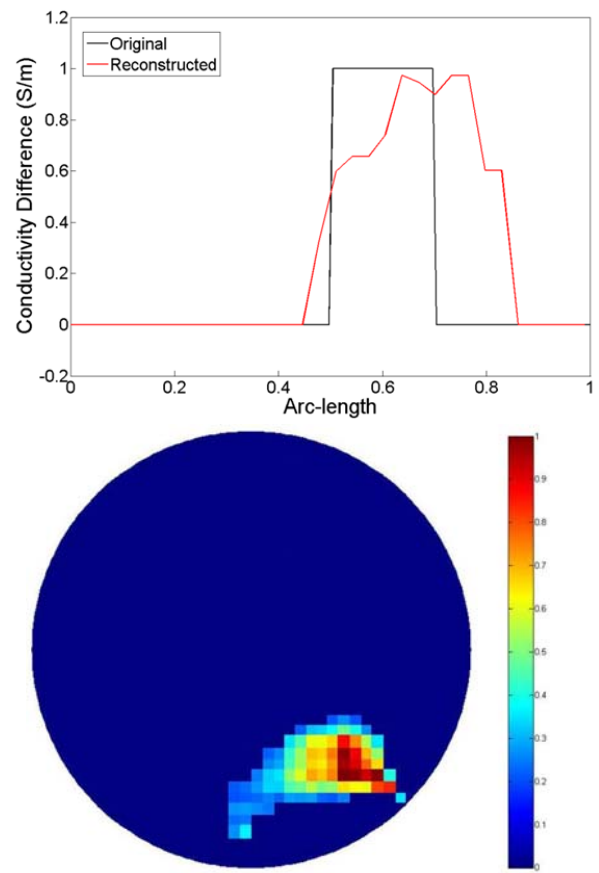Figure 6. DCP and reconstructed image of the haematoma on top of the left parietal lobe

Figure 7. DCP and reconstructed image of the haematoma on top of the right parietal lobe

4. Conclusion

Images of conductivity changes are successfully reconstructed with single anomalies in phantom model while the anomaly placed at the center and close to the edge of the tank. Simulated haematoma are also detected and localized in sheep's head. The experiment, in which simulated bleeding rate was monitored continuously, does establish that haematoma with a volume of less than 2ml can be quantified and detected. The exact position of the simulated haematoma could not be detected since the simulated blood was spread out inside the skull in the absence of cerebrospinal fluid and brain pressure, and its position was unknown. Therefore the simulated blood solution was transformed to gel with the same conductivity as blood and placed in a certain position. Simulated haematomas in sheep model were clearly detected and localised using our developed system. The presented results

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demonstrate that our EIT system is sensitive to the conductivity variation and has the potential to produce reliable and localized images from the boundary potential measurements. These phantom and sheep experiments prove that the detection and quantification of haematomas in the brain is possible and encourage further investigation for medical applications.

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