In-Vivo Detection of Bleeding Simulated in a Peritoneal Dialysis Model using a Hemiarray EIT Configuration

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Abstract. A new method to image and quantify intra-abdominal hemorrhage (IAH) using electrical impedance tomography (EIT) was tested. We proposed an electrode hemi-array placed exclusively on the anterior abdomen to monitor a supine patient for IAH without complicating concurrent traumatic injuries. Peritoneal dialysis (PD) was used as a model for IAH to assess the in vivo performance of the hemi-array. Using the EPack 2 data acquisition system, EIT measurements were recorded before, during, and after the administration of dialysate. Simultaneously, the amount of dialysate was recorded, synchronous to the EIT measurements, to be used as a control. Tomographic images of impedance change were reconstructed using a weighted, sensitivity-based method and then post-processed to obtain a quantitative estimate of the total dialysate administered. Our preliminary study included two subjects, one male and one female, each participating for two sessions, spaced about six months apart. Data collected from these sessions indicate that with a realized in vivo SNR of about 35dB the EPack 2 can detect accumulations larger than about 100mL with a quantification uncertainty of about +/- 50mL. Using these data we have developed new algorithms that can automatically detect the onset of bleeding in less than two minutes. This method shows promise for automated detection of other pathologies, e.g. ascites, and is adaptable for use on other anatomy including the skull, and pelvis.

1. Introduction
Intra-abdominal hemorrhage (IAH) is a life-threatening consequence of bomb blasts, motor vehicle accidents, building collapses and falls. Victims with mild IAH sometimes benefit from nonintervention and heal naturally. However, as total blood loss approaches one liter hypovolemic shock, ischemia and death are inevitable without surgical intervention. Rapid assessment of the amount of bleeding is therefore important.

The noninvasive modalities conventionally used to diagnose IAH are sonography [1] and computed tomography (CT). The former is rapid and somewhat portable and the latter has high sensitivity and specificity. Neither is well suited for continuous monitoring, and the accuracy of both methods depends on a technician well-trained in device operation and interpretation of the results.

Impedance-based methods detect IAH by exploiting the electric conductivity contrast of blood (0.67 S/m) and mean abdominal tissue (0.2 S/m). Tomographic images of dynamic bleeding are reconstructed using electrical impedance tomography (EIT), and post-processed to extract volumetric
estimates of the dynamic blood accumulation. This method is autonomous, continuous and does not require subjective operator interpretation.

Abdominal EIT has typically been recorded using 16 electrodes spaced equidistantly around the subject’s girth [2]. Sixteen-electrode EIT studies in both porcine [3] and human [4] models of IAH have concluded that bleeding rates exceeding 100mL/min were reliably detectable. But IAH is often accompanied by other traumatic injuries which limit responders’ ability to move victims. Accordingly, it is risky to place electrodes around the abdominal circumference without first evaluating concurrent injuries. Instead, in this study electrodes were applied only to the anterior abdomen accessible without moving a supine patient. The performance of the eight electrode hemiarray configuration has been tested in vitro [5]; herein we present preliminary in vivo results using this configuration.

Peritoneal dialysis (PD) is a useful model for simulating intra-abdominal hemorrhage. PD is an invasive procedure used to clear waste in patients with renal failure [6]. Dialysate solution is percutaneously introduced into the abdomen through a surgically placed catheter. The dialysate absorbs wastes that would normally be extracted by the kidneys, and is then drained.

2. Materials
EIT measurements were recorded using a hemi-circumferential electrode array designed to accommodate immobile patients. Carbon-loaded rubber electrodes (10x5cm) were equidistantly spaced on the anterior half of the abdomen, superior to the umbilicus.

The electrodes are connected to the EPack, a second generation, multiplexed EIT data acquisition system that is similar to the classic Sheffield Mark I [6]. The EPack has a DAC-driven, bipolar Howland current source that injects 1mA peak-to-peak current at 62.5kHz. A 14-bit digital voltmeter measures the magnitude of the complex voltage. The current source and voltmeter are multiplexed to eight electrodes via 1m coaxial cables with driven shields. The EPack collects and preprocesses measurement data, then wirelessly transmits the results to a Bluetooth-capable computer [8]. Data

![Image](image-url)

Figure 1. (Top) Reconstructions of dynamic dialysate accumulation at four interesting times. (Middle) The QI is calculated from each reconstruction frame and plotted as a time series. (Bottom) Time series plot of the amount of dialysate in the abdomen, the control variable. Vertical dashes represent the start and stop of fluid flow, respectively.
exchange is controlled by a graphical user interface (GUI) written in Visual C# 2008 (Microsoft, Redmond, VA).

3. Methods
Four subjects undergoing PD at the University of Florida’s dialysis clinic were recruited for the study. Of the four, two were excluded based on their medical history. The remaining two subjects, one male and one female, were each monitored using the EPack during a routine dialysis exchange. Six months later, subjects returned to repeat the experiment.

EIT recording at a frame rate of 1Hz was started after the electrode array was applied. Before dialysate infusion started, and after it was completed, a baseline no shorter than 10 minutes was recorded. After the baseline period, solution was allowed to flow into the abdomen. As dialysate drained into the abdomen, the mass of liquid remaining in the bag was weighed using a digital hanging scale with +/-0.2g precision. Recordings from the EPack and the scale were synchronized.

Images of the dialysate accumulation were reconstructed using a linearized sensitivity method described by Geselowitz [9] and Lehr [10]. The sensitivity matrix for the system was obtained by forward solution of two-dimensional electrostatic models created using COMSOL Multiphysics (COMSOL, Inc., Burlington, MA) in conjunction with MATLAB (MathWorks, Inc., Natick, MA) using the finite element method (FEM). The abdomen was assumed circular and uniformly conductive [11]. The pseudoinverse of the sensitivity matrix was calculated using truncated singular value decomposition (TSVD). Inspection of the L-curve was used to choose the regularization parameter, $\kappa=12$ [12]. Preconditioning the sensitivity matrix using the weighted minimum norm method proposed by Clay and Ferree generally improved reconstruction quality [13].

QI is the parameter used to estimate the volume of dialysate within an image. QI is the area-weighted sum of the pixels, $\Delta \sigma_j$, of a 2D EIT reconstruction,

$$QI = \sum_{j=1}^{n_P} A_j \cdot \Delta \sigma_j,$$

where $A_j$ is the area of the $j$th pixel, and $n_P$ is the number of pixels in the reconstruction. Here, images are of secondary interest, used to confirm the plausibility of volume change estimates.

Flow information was calculated by first smoothing the QI using a 120-point moving average filter. This reduced noise at the expense of a 120-sample delay. The derivative of the smoothed QI time series was calculated to obtain the flow rate as a function of time. Results of sensitivity analysis were used to convert flow rate from the arbitrary units of QI to SI units.

4. Results and Discussion
Preliminary results in both subjects are similar; representative results from one Patient 2, Trial 1 are illustrated in figure 1. Signal-to-noise ratio (SNR) was calculated during the static baseline over 100 voltage samples. Preliminary results indicate in vivo SNR levels on the

![Figure 2. Relationship between QI and mass of dialysate in the abdomen.](image)

### Table 1. Quantification sensitivity in two patients.

| Trial | Sensitivity (QI/kg) | Girth (cm) | Weight (kg) |
|-------|---------------------|------------|-------------|
| Patient 1 | 1 | 0.017 | 81 | 46 |
| 2 | 0.023 | | |
| Patient 2 | 1 | 0.024 | 112 | 78 |
| 2 | 0.024 | | |
order of 35-40dB, slightly lower than those observed \textit{in vitro} using saline tank phantoms. Baseline drift of QI corresponded to +/- 8g/min.

The dialysate flow rate was measured to decrease as the abdomen filled with dialysate and the dialysate bag emptied. This was also reflected in the QI results. Typically, dialysate accumulations in excess of 100g were distinguishable from background noise in image reconstructions.

The reconstruction algorithm is intended for accumulations as large as 1kg; beyond this range nonlinearity (decreasing sensitivity) in QI response was observed, as expected. Figure 2 shows the relationship between QI and the actual fluid mass for this range. QI had excellent linearity with respect to the control (0.94 < R² < 0.98). Table 1 compares the sensitivities across experiments. There was less dependence on anthropometric variation than expected. A communication glitch during Patient 1, Trial 1 limited the framerate half that used for other trials; this may explain that trial’s lower sensitivity.

In contrast with the sensitivity, the offset in QI varied considerably depending on the selection of the reference measurement. Differentiation of QI removed this offset and gave consistent results for each patient. Figure 3 shows the inferred flow data for Patient 2, Trial 1. The flow information is delayed by 120 seconds as a result of the smoothing filter. This estimate is useful for automatic detection of bleeding because it does not rely on careful selection of reference measurement.

5. Conclusion
Results presented herein are considered preliminary; due to the small sample size it would be premature to draw conclusions based on this data. Nevertheless, the results do illustrate the proof of concept and allow us to fine-tune our methods in preparation for larger data collection.

6. Acknowledgements
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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{flow_rate_measured}
\caption{Flow rate measured using EIT.}
\end{figure}