Effect of electrode arrangements on bladder volume estimation by electrical impedance tomography

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Abstract. The estimation of bladder volume by electrical impedance tomography is a promising technology to provide continuous volume estimates to patients who suffer from impaired bladder volume sensory. To find an optimized electrode arrangement for electrical impedance tomography of the human bladder, seven different electrode arrangements have been analysed using a finite element model. The arrangements under consideration can be assigned to three general groups: ring arrangements, linear arrangements and matrix arrangements. For each arrangement in these three groups, the condition of the Jacobian matrix and the global impedance for several bladder volumes has been calculated and compared using the EIDORS toolkit.

1. Introduction
Knowledge of current urine volume is of great interest to patients with paraplegia or those suffering from overactive bladder to determine the right moment for bladder emptying. One promising way to estimate current urine volume is by electrical impedance tomography (EIT). First EIT measurements using a circular electrode arrangement around the pelvis have shown a linear correlation of global impedance and bladder volume [1]. Still in question is, if a circular electrode array is the best arrangement to reach high sensitivity of the EIT measurement system. In FEM simulations of a four lead bioimpedance system, it could be shown that vertical electrode arrangements have increased sensitivity to bladder volume changes as compared with horizontal arrangements [2]. In contrast to lung EIT imaging, bladder impedance measurements have to deal with both impedance change and a shift of organ boundaries with increasing bladder volume: the bladder itself is a hollow muscle, located on the pelvic floor in the lesser pelvis. With increasing volume, the bladder stretches and extends upwards along the abdominal wall, displacing surrounding tissue. Although even a classical EIT ring array is able to measure impedance changes outside the electrode plane, an optimized arrangement will be much more suitable for quantification of bladder extension.

To find suitable electrode positions for bladder EIT, existing arrangements from literature have been reviewed. The most popular arrangement is the classical ring array, placing all electrodes around the thorax on the same level. This arrangement has been used by Leonhardt et al. for their bladder volume measurements [1]. This basic arrangement can be extended to the
third dimension by applying multiple rings in a fixed distance along the body axis. Graham and Adler showed good performance of this arrangement for lung EIT [3]. A similar arrangement using only ventral semicircles has been presented by Sadleir et al. [4]. Using ventral semicircles results in increased sensitivity in the ventral region in proximity to the electrodes, while dorsal regions show only small sensitivity. For bladder EIT, reduced sensitivity in the dorsal region might be advantageous to reduce influences of the rectum on calculated bladder volume. An electrode arrangement in vertical stripes has been presented by Murphy et al. [5]. Their system shows good resolution for conductivity gradients along the vertical axis. Configurations using some kind of matrix arrangement in the ventral half space have been presented by Hua et al. for spectroscopic measurements [6] and Erol et al. and He et al. for tomographic imaging [7, 8].

2. Materials & Methods
All calculations in this work have been conducted in Matlab using the EIDORS framework [9]. For a first evaluation of the electrode arrangements, a simple cylindrical tank model of 30 cm height and 15 cm radius has been used. Netgen has been used for meshing, producing a fine mesh for forward calculations of about 14,000 tetrahedral mesh cells. The background conductivity has been set to \( \sigma_{\text{b}},= 1 \text{ S/m} \). A sphere of variable radius and conductivity \( \sigma_{\text{sph}} = 2 \text{ S/m} \) has been used to model the bladder.

Two different locations have been used for the bladder sphere: in the first model, the bladder has been located in the centre of the tank. A more physiological arrangement has been used for the second model by locating the sphere at the bottom of the cylinder directly to the wall. With increasing volume, the sphere extends towards centre and top of the cylinder.

It has been shown in literature that image quality is highly dependent on the number of electrodes used [10]. Therefore, 16 electrodes have been used for all arrangements taken into consideration to focus on the influence of different arrangements only. A total of seven different arrangements have been evaluated that can be grouped into the categories of ring arrangements, matrix arrangements and vertical stripe arrangements. The arrangements described in the following paragraphs are shown in Figure 1.

In the group of ring arrangements, a classical 16 electrode ring at position \( z = 0.15 \) in the middle of the cylinder, two rings of eight electrodes at positions \( z = 0.1 \) and \( z = 0.2 \), as well as four rings of four electrodes at positions \( z \in \{0.06, 0.12, 0.18, 0.24\} \) have been used. Adjacent excitation has been used to stay compatible with the Goe MF II device.

In the group of matrix arrangements, a model with two ventral semicircles of eight electrodes comparable to the arrangement of Sadleir [4] and a matrix of \( 4 \times 4 \) electrodes comparable to the arrangement of Hua [6] have been used. Adjacent excitation in horizontal direction has been used as well.

The last two arrangements are inspired by Murphy et al. [5] with one model having two vertical stripes of eight electrodes on opposite sides of the cylinder wall, and a model using two stripes of four electrodes on each side. Excitation between adjacent electrodes on the same
Figure 2: Relative decrease of singular values

z-level has been used which results in a polar through measurement for the $2 \times 8$ stripes model and an alternating change of adjacent and polar for the $4 \times 4$ stripes model.

In general, the GREIT algorithm available in EIDORS has been used to find a reconstruction matrix for all models. Unfortunately, we did not succeed to compute a GREIT reconstruction matrix for the vertical stripes models, so basic Gauß-Newton reconstruction has been used for these two models.

The performance of each arrangement has been evaluated by comparing the normalized singular values of the Jacobian matrix and by comparing global impedances for varying bladder sphere volumes. The Jacobian matrix $J$ describes how an impedance change of a single mesh element influences the boundary voltage measurement. Analysing the singular values provides a measure for the condition of $J$ [10], which is linked to reconstructed image quality. An electrode arrangement is considered to be good, if the singular values are decreasing slowly. To compare the performance of bladder volume measurements, the global impedance has been calculated for 14 sphere radii from 1 cm to 14 cm, referenced to a baseline measurement of an empty tank.

3. Results

The singular values in Figure 2 are normed to the first singular value $\sigma_1$ for better comparison, as suggested by Tang et al. [10]. The slowest decay of singular values show the single 16-electrode ring, the ventral semicircles and two rings of eight electrodes. The best condition number, which is the ratio of greatest to smallest non-zero singular value, is provided by the ventral semicircles arrangement.

The sensitivity to bladder volume changes, as depicted in Figure 3, is highest for the two three dimensional ring arrangements "Ring $2 \times 8$" and "Ring $4 \times 4$". Ventral semicircles and the $4 \times 4$ matrix model show also a strong bladder-related impedance change. The global impedance results of the two vertical stripes alignments can not be compared directly, since they are based on a different reconstruction method.

All arrangements except the single 16 electrode ring and the vertical stripes arrangements are very robust with respect to bladder position, which means that there is only little difference in global impedance for both bladder positions as described in section 2. Especially for bladder
Comparison for bladder in electrode plane

Figure 3: Comparison of global impedance

radii of a few centimetres, the single ring arrangement shows high error. Using two rings of eight electrodes results in a much more homogeneous sensitivity, which produces more stable results. The results for "Ring 4 × 4", matrix and semicircles are comparable.

4. Conclusion

Seven different electrode arrangements of 16 electrodes for 3D EIT measurement of the human bladder have been evaluated using a simplified FEM-model using EIDORS and NetGen. The arrangements have been rated by analysing the decay rate of singular values and by comparison of the correlation of global impedance and volume for simulated EIT measurements. It could be shown that a single 16 electrode ring, as usually applied for lung EIT measurements, may not be optimal for reliable bladder tomography. Instead, multiple ring and ventral semicircle arrangements seem to yield better electrode topologies for this application.

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