Internal Electrode Bladder Volume EIT for routine urodynamic test application: An FEM study using EIDORS framework

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Abstract. *Electrical impedance tomography measurements of the lower abdominal region have shown a strong correlation with bladder volume. A potential application of this technique is its integration into the routine urodynamic test, during which an intraurethral catheter is commonly used to infuse fluid of known conductivity into the bladder. The use of an internal EIT electrode integrated into the catheter might improve the accuracy of the volume estimation by increasing the sensitivity of the measurement directly in the bladder region. In this paper, a first approach of the system is analyzed and compared to the standard 1x16 ring electrode arrangement by means of an FEM-model. The conductivity contrast of the model is varied by changing the background medium conductivity (relative conductivity range from 0.25 to 4), while keeping bladder conductivity constant (relative conductivity of 2). Simulated EIT data is obtained for twenty discrete bladder volumes between 50 mL and 700 mL. A linerl regression is fitted to the data in order to estimate bladder volume from the simulated EIT-data using the Global Impedance (GI) method. The use of an internal electrode seems to make the measurement less susceptible to background conductivity changes which increases the accuracy of the method.*

Keywords

Bladder volume estimation, global impedance, internal electrode, urodynamic test, EIDORS framework.

1. Introduction

Electrical impedance tomography (EIT) offers a potential non-invasive, continuous measurement of bladder volume. In fact, a strong linear correlation between the measured lower abdomen global impedance (GI, see section 2.3) and bladder volume has been shown [1], as depicted in Figure 1. This is feasible due to the fact that urine conductivity is usually greater than the conductivity of surrounding tissue. Such a system would prove especially beneficial for those patients who experience a reduced sensitivity to bladder fullness. This is the case, for example, of paraplegic patients who, depending on the degree of neural damage, may even experience a complete lack of urinary function and need to empty their bladders under a fixed-time self-catheterization scheme. If the bladder is emptied too early it unnecessarily decreases the quality of life of the patient by increasing the number of times the self-catheterization procedures, while also increasing the risk of an infection. On the other hand, if the bladder is emptied too late, the patient experiences discomfort such as excessive sweating as well as increasing the risk of complications such as over-distension of the bladder wall, hydronephrosis or autonomic dysreflexia [2]. A portable, continuous bladder monitoring system, as shown in Figure 2, would provide the possibility of a patient specific demand-driven bladder emptying scheme.

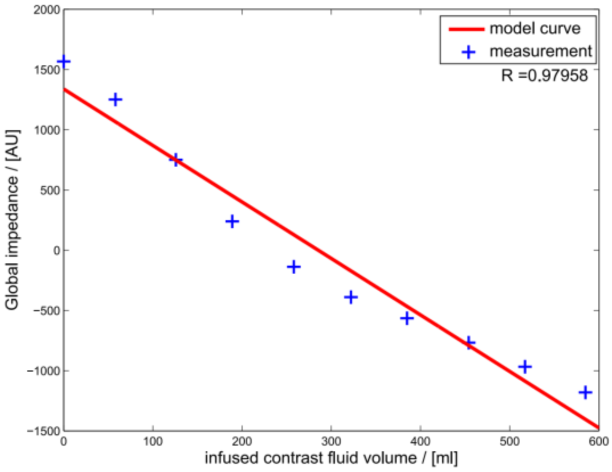

Fig. 1. Correlation between lower abdomen global impedance (GI) and bladder volume. GI decreases as bladder volume increases. Taken from [1].

Another patient collective that would benefit from this system are those suffering from a condition known as overactive bladder syndrome (OBS). In this case the urge to urinate onsets too early, even though the bladder is physically capable of holding more urine volume. These patients undergo physical and psychological therapy in order to progressively train the bladder to gradually hold more urine before micturition. In this case, the device could be integrated into the training program, allowing the patient to obtain real-time feedback on their bladder current full-status and confidently decide when to urinate.

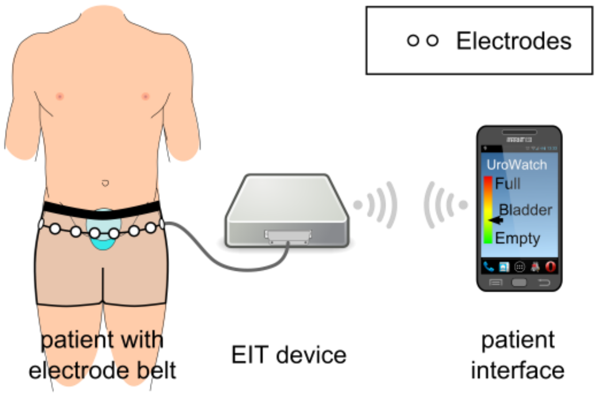

Fig. 2. EIT- Bladder volume monitoring system

Previous work has focused on the development of this system, including the determination of optimal electrode arrangement as well as identifying and compensating different sources of error in the measurement such as body posture and body movement. Variable urine conductivity, which depends on daily food and liquid ingestion and the activity level of the subject, is unknown. Since EIT measures the conductivity distribution in the body, the unknown urine conductivity has a considerable negative impact in the measurement technique. Some methods have been proposed to compensate urine variability [3].

1.1 Urodynamic test

For the proposed EIT system an initial, individual patient calibration would be necessary. This could be performed during a routine urodynamic test, a diagnostic procedure to assess lower urinary tract dysfunction. It may include some or all of the following tests:

1. Uroflowmetry: Measurement of the voluntary urination flow rate.
2. Post-void residual urine (RU) measurement: Measurement of the reamining urine volume after voluntary urination. This can be done non-invasively via Ultrasound (US), or by emptying the bladder completely via an intraurethral catheter.
3. Cystometric test: Pressure measurements inside the bladder via a catheter. The bladder is slowly filled while recording rectal and cystometric pressures, as well as patient feedback with respect to urination urgency sensation.
5. Leak point pressure measurement: The pressure inside the bladder is recorded at the point when involuntary urine leakage occurs.

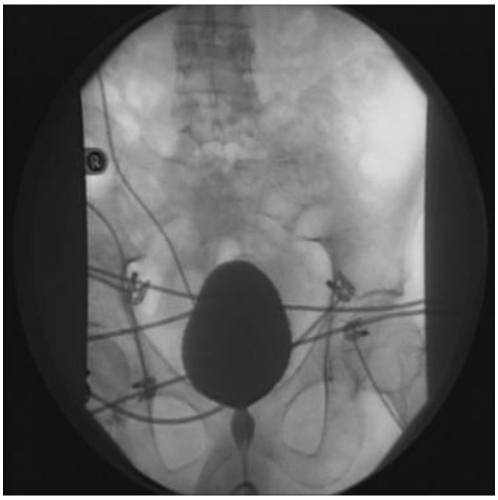

Fig. 3. X-Ray image of the bladder and intraurethral catheter. The IU catheter is visible only outside the bladder, since the contrast fluid is radio-opaque.

Urodynamic testing usually involves the use of an intraurethral (IU) catheter for bladder filling and/or emptying, and pressure measurements. Therefore, it may be feasible to integrate an EIT electrode on the catheter in order to provide increased EIT sensitivity within the bladder region. In addition, the infused contrast agent is of known conductivity which allows the negative influence of varying urine conductivity to be avoided. Figure 3 shows an X-Ray image of a patient with an IU catheter inside the urinary bladder.

1.2 The gold standard: Ultrasound

The ultrasound technique is currently the gold standard for bladder volume estimation. However, it cannot be performed continuously. Furthermore, it has been shown that it has a relatively low accuracy in maximum bladder capacity (BCmax) and residual urine (RU) estimation, with maximum correlation in the order of 68 % to actual bladder volume [4].

2. Materials and methods

2.1 Electrical Impedance Tomography

The EIT technique consists of high frequency and low amplitude (usually 5 mA at 50 kHz) current injection into the body and measurement of the resulting voltages at the surface through a specific electrode arrangement. It has been mainly developed for lung ventilation monitoring, since the high conductivity contrast between inhaled air and surrounding tissue allows for a real-time evaluation of regional lung ventilation in critical-care patients. Furthermore, the extraction of cardiac perfusion parameters from the EIT signal is an ongoing area of research.

2.2 EIT image reconstruction

EIT image reconstruction is an ill-posed, nonlinear inverse problem [5]. Several methods have been introduced, from which the Graz consensus reconstruction algorithm for EIT (GREIT) is well accepted within the EIT community and is used in this study to calculate the reconstruction matrix (**R**) [6]. Furthermore, since absolute EIT measurement is particularly challenging, as it demands for exact prior knowledge of geometry and electrode positioning, most applications are based on differential EIT, in which the measured voltage data of the homogeneous body medium (υ_h) is used as a reference measurement. If we consider the measured surface voltage (υ_i), then:

$$b = \left[\frac{[v]_i - [v]_h}{[v]_h} \right] \tag{1}$$

$$\hat{i} = \mathbf{R}b \tag{2}$$

where **R** is a reconstruction matrix that maps the normalized voltage difference measurements (b) to an image matrix **î**. For this study, 16 electrodes are considered. There is no voltage measured through the drive electrodes which gives a total of 208 (16 x 13) voltage measurements per EIT frame. The reconstructed image consists of 32 x 32 pixels, which means the reconstruction matrix has dimensions of 1024 x 208. The reconstruction matrix is calculated in Matlab using the EIDORS framework and GREIT.

2.3 Global Impedance

After obtaining the impedance distribution 32 x 32 tomographic image, and in order to extract a bladder volume estimation, the global impedance is calculated. It consists of the algebraic sum of all pixel values in a single EIT frame, as shown in figure 4.

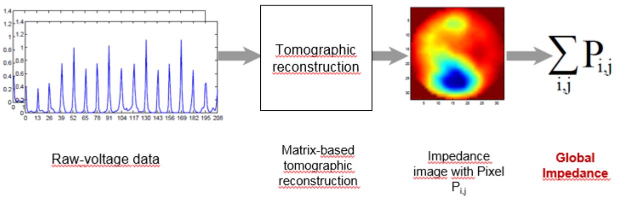

Fig. 4. From the raw EIT voltage data, a matrix-based tomographic reconstruction is performed. The single pixel values are then summed to give a global impedance value for a single EIT frame. Taken from [7].

2.4 Electrode arrangements

In lung ventilation monitoring, the 16 electrode ring arrangement is commonly used. For the bladder EIT, this arrangement has been shown to provide an acceptable compromise between bladder region sensitivity and background conductivity variation.

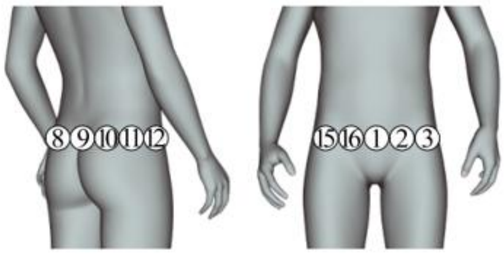

Fig. 5. Standard 1x16 electrode ring arrangement for adjacent injection and measurement pattern.

For this study, an alternative arrangement (Electrode arrangement 2) is proposed. Electrode number 9, located normally on the back of the subject (Fig. 5), is removed and placed inside the bladder, simulating an internal electrode on an IU catheter. This is depicted in the FEM-mesh in Figure 8.

2.5 FEM-Model

A simplified FEM-model was created using the EIDORS framework and NETGEN, an open-source mesh generator [8]. The model geometry consists of a cylinder of diameter (ϕ) 30 cm and height (h) of 30 cm. The electrode plane is positioned at a height of z_1 = 5 cm, as shown in Fig. 6. The bladder is represented by an eccentrically placed sphere, since the bladder is located in the pelvic frontal region. This FEM-model was used to calculate the reconstruction matrices for both electrode arrangements, EA1, the standard 1x16 ring and EA2, the modified 1x15 ring with 1 internal electrode arrangement.

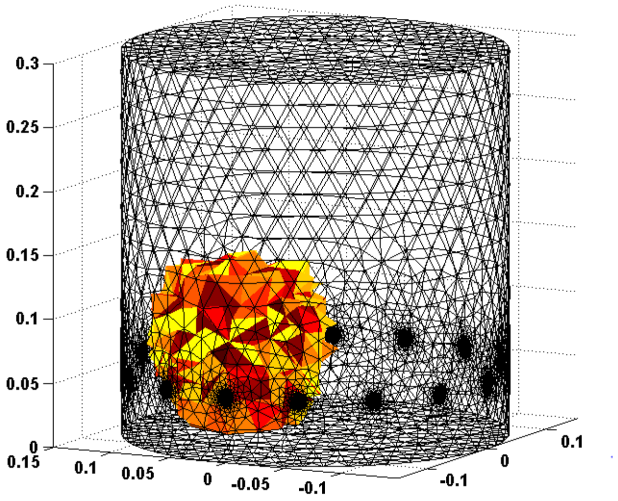

Fig. 6. 3D view of the cylindrical mesh used for the forward solver. The mesh elements are finer at the electrode surfaces due to the expected higher current density at those sites.

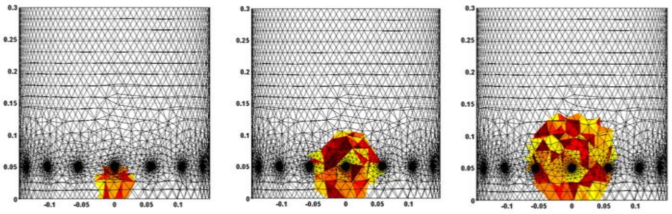

Fig. 7. Three different bladder volumes as generated with EIDORS and NETGEN. From left to right, bladder volumes of: 50 mL, 400 mL, and 1000 mL. To simulate the physiological bladder filling process, the bladder position is generated as a function of its radius, and remains in contact to the cylinder floor.

The bladder is anatomically located on the pelvic floor. During bladder filling, it expands upwards. Its volume ranges from a few millimeters to up to 700 mL - 1000 mL, depending on the individual's BCmax. To simulate this physiological filling characteristic more accurately, the bladder position is defined in the FEM-mesh geometry as a function of its radius, to guarantee that it is always in contact with the cylinder base, as seen in Fig. 7. Furthermore, The FEM-model for electrode arrangement 2, in which electrode 9 is positioned inside the bladder as an internal electrode, can be observed in Fig. 8. For visualization purposes, the bladder is not depicted.

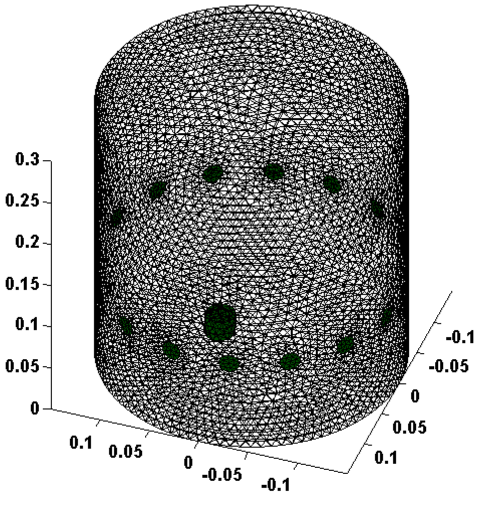

Fig. 8. 3D view of the FEM-model for the internal electrode arrangement. The bladder is not depicted for visualization purposes.

Simulated EIT Data was obtained for 20 bladder volume values, ranging from 0 to 1000 *ml*, and 5 different relative background conductivities, ranging from 0.25 to 4.0. The global impedance was calculated after an intermediate tomographic reconstruction stage using the GREIT algorithm.

The results relating bladder volume to GI for conductivity contrast of 2 (bladder conductivity of 2 and background conductivity of 1) were fitted with a linear regression which was then used for the remaining volume estimations at the different background conductivities.

3. Results and discussion

The results are summarized in Table 1. The relative volume estimation error for different conductivity contrast and different bladder volume is given in [%]. The upper values correspond to the standard 1x16 electrode ring arrangement while the lower values correspond to the internal electrode arrangement.

Relative conductivity contrast		0.25	0.5	1	2	4
bladder volume [ml]	100	97%	45%	44%	98%	59%
		-91%	68%	64%	60%	103%
	200	-80%	92%	33%	75%	-58%
		77%	72%	17%	38%	45%
	400	16%	14%	35%	25%	18%
		21%	25%	24%	-27%	-17%
	600	21%	5%	42%	18%	27%
		-8%	10%	-14%	12%	13%
	800	-14%	18%	-12%	-20%	38%
		9%	-10%	3%	10%	-1%
	1000	-10%	8%	4%	5%	-2%
		-9%	12%	2%	-8%	-5%

Tab. 1. Relative bladder volume error expressed in % with respect to actual volume, for the standard 1x16 electrode ring arrangement (EA1, shaded upper value) and the internal electrode arrangement (EA2, non-shaded lower value).

Both methods show high errors at low bladder volumes, probably due to the fact that, as mentioned in section 2.5 and depicted in Fig. 7, in order to more accurately represent the human anatomy, the simulated bladder is always in contact with the cylinder bottom, and its position is a function of its radius. Therefore, at lower volumes, the bladder is off-plane with respect to the electrode ring, which has an impact in the measured voltages, calculated GI and estimated bladder volume. Overall it can be concluded that the internal electrode arrangement outperforms the standard 1x16 electrode ring arrangement in this simplified geometry FEM simulation model.

4. Outlook

The potential application of an internal electrode arrangement for EIT bladder volume estimation during routine urodynamic shows good promise. In this study, the simplified FEM analysis was limited to a single internal electrode. However, in practice, more electrodes could be integrated into the catheter. Further work will be focused on determining optimal internal electrode number and arrangement for this system, as well as further FEM simulations with anatomical models.

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