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Parametric electrical impedance tomography for measuring bone mineral density in the pelvis using a computational model

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ABSTRACT

Osteoporosis is defined as bone microstructure deterioration resulting a decrease of bone's strength. Measured bone mineral density (BMD) constitutes the main tool for Osteoporosis diagnosis, management, and defines patient's fracture risk.

In the present study, parametric electrical impedance tomography (pEIT) method was examined for monitoring BMD, using a computerized simulation model and preliminary real measurements. A numerical solver was developed to simulate surface potentials measured over a 3D computerized pelvis model. Varying cortical and cancellous BMD were simulated by changing bone conductivity and permittivity.

Up to 35% and 16% change was found in the real and imaginary modules of the calculated potential, respectively, while BMD changes from 100% (normal) to 60% (Osteoporosis). Negligible BMD relative error was obtained with SNR > 60 [dB]. Position changes errors indicate that for long term monitoring, measurement should be taken at the same geometrical configuration with great accuracy. The numerical simulations were compared to actual measurements that were acquired from a healthy male subject using a five electrodes belt bioimpedance device.

The results suggest that pEIT may provide an inexpensive easy to use tool for frequent monitoring BMD in small clinics during pharmacological treatment, as a complementary method to DEXA test.

1. Introduction

1.1. Osteoporosis and fractures

One of the most common diseases in the world today is Osteoporosis (OP). It is defined as abnormal loss of bone mineral density (BMD) which leads to a deterioration of the bone microstructure and hence a decrease of bone strength [1]. Bones are composed of two types: cortical, the hard outer layer, and cancellous, filling the interior of the bone, gives it rigidity and a coral-like three-dimensional internal structure. Osteoporosis results from a period of asymptomatic skeletal bone loss and hence reduced bone strength, predominantly in cancellous bone. The cancellous bone microstructure gets thinner and more fragile as well as porosity increase. These two processes result in structural instability and increasing fracture risk [2]. Worldwide, Osteoporosis causes about 9 million fractures annually, mainly of the pelvis (hip), spine, and wrist. It has been estimated that 1 in 3 women over 50 will experience osteoporotic fractures, as will 1 in 5 men [3–5].

Today, according to the World Health Organization (WHO), BMD measurements are the main tool for prevention, diagnosis and management Osteoporosis and also the standard to address the risk of osteoporotic fracture [6]. A 10% bone mass loss in the pelvis results in a 2.5 times greater risk of hip fracture [7]. Dual X-ray absorptiometry (DXA) measurements of BMD have been universally adopted as a standard to define osteoporosis. However, given the limitations of DXA BMD measurements, the WHO recently introduced the FRAX tool (available at www.sheffield.ac.uk/FRAX/) to better evaluate fracture risk of patients. Moreover, fracture risk is considered to be affected by prior fractures, rheumatoid arthritis, bone quality and patient's basic physiological data in addition to BMD value [7,8].

As life expectancy increases, the population percentage with OP fractures grows. By 2050, the worldwide incidence of hip fracture in men is projected to increase by 310% and 240% in women [9].

1.2. Four disease stages

In 1993, WHO determined BMD loss diagnosis criteria to be measured as BMD deterioration from mean of the young adult reference range [10]. A 30-year-old woman's BMD is defined as *T* score, 100%. Disease stages are stratified according to the *T*-score

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(*T*) change in standard deviation (SD): normal BMD (*T*-1>, 90%>), mild Osteopenia (*T*-1.1–*T*-1.5, 90–85%), moderate Osteopenia (*T*-1.5–*T*-1.99, 84–75%), advanced Osteopenia (*T*-2–*T*-2.5,74–70%), and Osteoporosis (*T*-2.5<, 70%<) [11–13].

Both sexes have almost equal BMD values before bone lose; however, the density of the two bone components, the cortical and cancellous, varies differently in BMD loss for each sex. In men, the cortical density dilutes to about 80% of its optimal value and the cancellous density dilutes to about 60% of its optimal value in OP [14–16]. Based on Dinc et al. [15], the density values' variations from mean peak bone density (100% BMD) to OP density (60% BMD) are as follows:

$$0.2356 < \rho_{cortical} < 0.3366 \left[\frac{g}{cm^3}\right] \quad (1.1)$$

$$0.0855 < \rho_{cancellous} < 0.171 \left[\frac{g}{cm^3}\right] \quad (1.2)$$

where ρ is bone density; higher values define healthy bone density and low values, 80% and 60% of healthy cortical and cancellous BMD values, respectively, are defined as OP.

1.3. Screening test

Currently, the most commonly used test is dual-energy X-ray absorptiometry (DEXA) of the hip and lumbar spine. BMD screening test, using DEXA, is recommended for menopausal women and men over 65, or on younger women whose fracture risk is equal to or greater than that of a 65-year-old white woman who has no additional risk factors [17]. The DEXA testing has several disadvantages; it is a relatively expensive procedure, it uses large and static equipment that is usually located in a hospital and it involves ionizing radiation. Moreover, the U.S. preventive services task force [17] concluded that limitations in testing precision require a 2 years minimum gap for reliably measure a significant change in BMD; and longer intervals may be necessary to improve fracture risk prediction [12,17,18]. This limitation makes this method not suitable for frequent testing and for follow-up medicinal treatment.

In 2003, electrical measurements done in bovine trabecular bone samples showed excellent correlations between electric and mechanical properties and BMD measurements [19]. Thus, evaluating the bone dielectric properties can assist predicting bone's strength and quality related to bone mineral density. However, fracture risk can be affected also by bone quality and patient's basic physiological data in addition to BMD value [7,8].

Bioimpedance techniques enable monitoring tissue dielectric propertied. These methods are based on the physical principle that varied electrical properties can indicate varied geometrical and mechanical tissue properties. Safety regulations and technical issues limit the current applied by EIT systems. The injected current is alternating in frequency ranging between 1 kHz to 2 MHz. Its RMS amplitude is limited to 100 μA–10 mA depending on the stimulating frequency.

Several modalities of bioimpedance technique are being used: the coil induced currents [20,21], the basic injected current electrical bioimpedance [22–24], and the electrical impedance spectroscopy [25–27]. These techniques use only the forward solution and do not image the spatial distribution within the human body.

Another modality, electrical impedance tomography (EIT), is a non-invasive imaging method [28–32]. This method involves two phases – a forward solution and an inverse solution. The forward solution involves applying alternating electrical current to the body, by direct injection via attached skin electrodes, which develop surface electrical potentials. From the measured potential using several projections, information about the inner bioelectrical properties distribution can be extracted using the inverse solution.

Table 1
Human tissue's conductivity and relative permittivity values at excitation frequency of 100 kHz.

Tissue	Conductivity, σ [S/m]	Relative permittivity, ε_r
Blood	0.7	5236.5
Bladder	0.2189	1231.1
Bone marrow	0.0028959	374.18
Bone cancellous	0.082946	1005.8
Bone cortical	0.020513	362.08
Colon + rectum	0.24	7429.2
Fat and soft tissue	0.024414	92.885
Muscle	0.345	15,521
Prostate	0.43861	5717
Skin	0.065	15,357

In the present study, the feasibility of the parametric electrical impedance tomography (pEIT) technique, that uses small number of electrodes and enables frequent measurements in small clinics to monitor BMD, is investigated. This technique may help in follow up medical treatment for osteoporotic between DEXA measurements.

2. Methods

2.1. Electrical parameters

EIT method is based on the physical principle that biological tissues differ from one another by their electrical properties: conductivity – $\sigma[\frac{Sym}{m}]$ and permittivity – $\varepsilon[\frac{F}{m}]$. Both are the components of the complex conductivity of each tissue type:

$$\sigma_{tissue} = \sigma + i\varepsilon \quad (2)$$

The two electrical properties are unique for each tissue type, and are frequency depended of the applied currents [33,34].

In the present study, each tissue type was considered homogenous; leading to representing each complex conductivity value as the mean of a tissue substance. Observing each tissue bulk as homogenous instead of individual voxels, defines a method with a small number of unknown parameters called parametric electrical impedance tomography (pEIT) [35–37]. The conductivity and permittivity values of relevant human tissue types at frequency excitation of 100 kHz are shown in Table 1 [38–41]. Since changes in the bone conductivity and permittivity values occur due to changes in BMD, it can be used for monitoring BMD.

2.2. Forward problem algorithm

In the forward phase, the electrical potential distribution is calculated from the known current source and tissues electrical properties (eq. 3). For this solution, the Poisson equation is solved using FVM numerical system for 3D discretization [22,42]:

$$f\left(\sigma, \vec{J}_{source}\right) = \emptyset \quad (3)$$

where f represents the forward function, J represents the current source and $\emptyset$ represents the surface potential. The phasor formulation of Maxwell's equations describes the behavior of sinusoidal electric and magnetic fields in a general medium. The model assumptions in this work are: (a) biological tissues are non-magnetic and isotropic media, (b) for chosen field frequency for 100 kHz and at current density of 1 $[\frac{A}{m^2}]$, biological tissues can also be assumed linear and isotropic (ε, μ, σ are scalars) [43], (c) considering the electrical field as conservative (quasi-static approximation), and (d) No coupling between electric and magnetic fields. Using these assumptions and vector identities the Poisson's equation can be written (Gauss' theorem) [31]:

$$\nabla \cdot [(\sigma + j\omega\varepsilon)\nabla\emptyset] = \begin{cases} -I_v & \text{on electrodes} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

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