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Original Article

# Electromagnetic simulation of non-invasive approach for the diagnosis of diabetic foot ulcers

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A R T I C L E I N F O

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A B S T R A C T

Diabetic foot ulcers are systemic diseases that affect all blood vessels within the human body. From major blood vessels to microvasculature, hardening, thickening, and narrowing of blood vessels ultimately results to diminished blood flow to end organs. The detrimental effects of peripheral vascular disease are well recognized across medicine, particularly with regards to diabetic foot ulcers. Diabetic foot ulcers (DFU) are common across all fields of medicine, including but not limited to: orthopedics, vascular surgery, podiatry, general internal medicine, and infectious disease. As the population of the United States continues to grow in age and obesity, diabetes and DFU are becoming more and more prevalent in our medical society. Current approaches to diagnosing peripheral vascular disease ultimately result in some degree of invasiveness for the patient. Preliminary lab studies, such as the ankle-brachial index and Doppler ultrasound of peripheral arteries, provide efficient safe screening methods. However, these studies lack quantification of the degree of vascular stenosis and are unable to accurately assess the location of narrowing. In current practice, radiologists are called upon to for angiography of the blood vessels using contrast dye. This provides an additional risk for diabetic patients: a population inherently at risk for renal disease.

In this study, we proposed utilizing electromagnetic simulation with boundary conditions set at various layers of human tissues. More specifically, the human foot was analyzed using COMSOL multi-physics software in attempt to visualize, analyze, and quantify the degree of peripheral vascular disease, which plays a pivotal role in the development of diabetic foot ulcers. The simulation was conducted for a patient's foot, with bone, blood vessels, and surrounding fat layers to emulate the anatomy of a diabetic foot. A 2-D scan was obtained to assess and visualize the blood vessel's narrowing, widening, vascular turbulence, or occlusion. The analysis was conducted at two frequencies, 2 GHz and 5 GHz, and compared to one another to assess the accuracy of clinical diagnosis. An electric field was generated throughout the 2D model at 20, 50, and 100 Joules, respectively. The simulation was able to adequately predict and stratify varying degrees of occlusion within peripheral vasculature. This study, though a simulation in nature, shows promise for being able to accurately diagnose the peripheral vasculature using electromagnetic parameters. This feasibility study proved successful for possible future implementation using MEMS/NEMS device systems to be designed to detect EM parameters to serve as a diagnostic tool for the early detection of peripheral vascular disease, and ultimately, diabetic foot ulcers.

## 1. Introduction

Human Arterial system is a blood circulation feeding various body members, and may be affected by narrowing, widening, or blocking the blood path at any section in the arterial system.[1] The blocking of the artery may be attributed to cholesterol deposits within the vein's boundary. This is known as atherosclerosis (the narrowing of veins). [1] This may result in painful or numbness foot, and may lead to ischemia of the foot.[2] This may be seen often in diabetics and orthopedic patients.[3] In normal patients, this may occur when there is no adequate blood flow, leading to sore development,[4] which is frequently managed by orthopedic surgeons. In orthopedic, patients may suffer from muscle weakness and/or brittle bone. Varicose veins (Large cross-sectional area) may cause inability to maintain a regular blood flow within the blood circulation of the human system.[5] Less resistive flow in large veins/ varicose veins may imbalance affecting the blood flow from the source (heart). Varicose veins may cause chronic swelling in the foot, and ankles among others.[6] A serious issue that may occur from the vein

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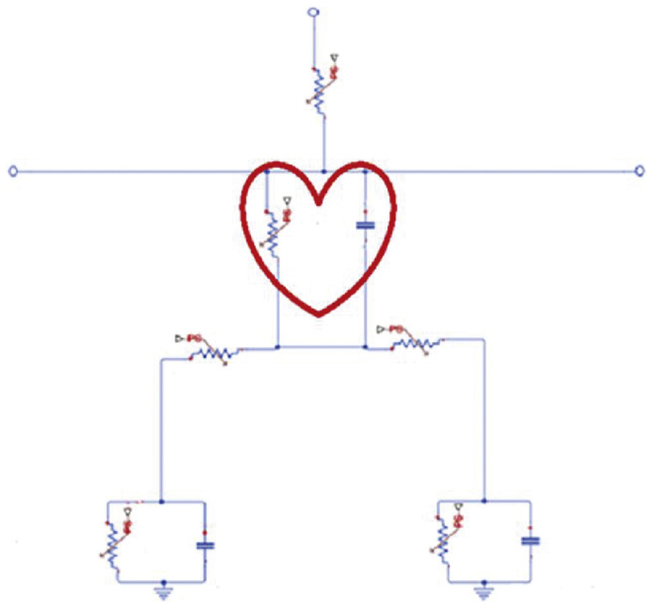

**Fig. 1.** The circuit model of blood circulation within the human body.

narrowing is the blood clots that may lead to some pulmonary disease which could be life threatening to the patients.[7]

The impact of the blood vessels widening and narrowing can be easily understood from the circuit model such as the one shown in Fig. 1.[8] If a vein is narrowed within the blood circulation, this is equivalent to a higher resistance that may affect the blood flow near the artery (the source). Likewise, if a vein is widened, this will be equivalent to a reduction in the resistance for the blood flow, leading to a higher blood flow drawn from the source. In either case, this may affect the output performance of the human heart.

Treatment of vein problems may need general surgery or invasive approach such as vascular surgery or inferential cardiovascular surgery. Medications are currently used in order to reduce the effect of blood vessels narrowing but may temporarily be reducing pain or dissolving clots. Medical imaging has been used for the investigation of vein narrowing in order to address the seriousness of the disease. Among those are ultrasound or ultrasonography[9] in identifying symptoms and causing signs of blood narrowing or artery narrowing.[10] However, the Sonographic Elasticity imaging (SEI) is a noninvasive approach, it cannot assist the maturity of the case and cannot detect the chronic clots.[11] CT and MRI are commonly used as tools to visualize the central veins or test the presence of complications in Pulmonary Diseases. [12] The cost and accuracy involved in this tool sets limit to their application within the human foot.

In this study, we propose electric field scanning on the surface area of the foot skin, ankle, or others to detect the narrowing, widening, and blocking within veins via the blood circulation system. The simulation done here was by applying two high energy levels (10 J and 100 J energy) at 3 and 5 GHz values. The transmission properties of the electric field distribution between layers, and among the veins, bones, and skin, lead to the determination of the field parameters.

## 2. The EM models

The wave equation used in the determination of the E distribution is given below:

$$\nabla \times (\nabla \times E) = \nabla (\nabla . E) - \nabla^2 E$$

From Gauss 'law, $\nabla . D = P_v$, then $\nabla . E = P_v/\varepsilon$

Using $P_v = 0$, the wave equation becomes:

$$\nabla \times (\nabla \times E) = -\nabla^2 E$$

The electric field is given in the form:

$$E = E_0 e^{-\gamma z}$$

where $\gamma$ = Propagation constant determined from:

$$\gamma^2 = -\omega^2 \mu \hat{\varepsilon}$$

where $\hat{\varepsilon}$ is the complex permittivity given as:

$$\hat{\varepsilon} = \varepsilon(1 - j\sigma/\omega\varepsilon)$$

when $\varepsilon = \varepsilon_0 \varepsilon_r$

$\omega = 2\pi f$

$\sigma$ = conductivity

The propagation constant, $\gamma$, is given by:

$$\gamma = \alpha + j\beta$$

Where $\alpha$ is the attenuation constant, and $\beta$ is the Phase shift constant. The electric field is then given by:

$$E = E_o e^{-\alpha z} e^{-j\beta z}$$

The magnitude of the field is given by:

$$E = E_o e^{-\alpha z}$$

The boundary conditions used in this analysis were based on matching the tangential components of the electric fields at the interfaces, fat/vein/bone boundaries. That is nxE = 0 at the interfaces.

## 3. Results and discussions

The research conducted here covers data for normal patients "all veins have the same size" as well as patients with vein issues disease (such as narrowing, widening, and missing). The study considers a foot size of 10 cm × 20 cm × 1 cm about 160 steps were generated from the software to track the electric field changes across the fat, bone, and vein materials. Initially 3 GHz signals simulation can be used to detect the presence of the veins. Based on the results of 3 GHz signal results we can implement 5Ghz signal simulation to measure the thickness of the veins. Table 1 gives the material properties used in the simulation

### 3.1. The mesh graph

Fig. 2 shows the computer mesh model used in the simulation with finer mesh of 0.5 m m to 1 m m. This mesh was used to get better accuracy of the field distribution output.

### 3.2. Vein detection for Normal patients

COMSOL simulation was conducted to detect normal patient condition with all veins having the same size. The veins were surrounded by fat materials. The electric field distribution across the fat showed maximum value, while inside the vein was minimum. The size of the veins was easy to detect since they are surrounded by fat materials from both sides. In this study also, we considered two different frequencies,

**Table 1**
Material properties used in the simulation.

| Material | Frequency | Relative Permittivity | Conductivity (mho/m) |
|---|---|---|---|
| Bone | 2 GHz | 4.9 | 0.15 |
| | 5 GHz | 0.8 | 0.21 |
| Muscle | 2 GHz | 55.4 | 1.45 |
| | 5 GHz | 49.6 | 2.56 |
| Fat | 2 GHz | 15 | 0.35 |
| | 5 GHz | 12 | 0.82 |