

Simulation of Electrode Impedance and Current Densities Near an Atherosclerotic Lesion

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Abstract—A four-point electrode measuring impedance in the vicinity of an atherosclerotic lesion was modeled using FEM software. The simulation modeled the electrodes as being attached to an angioplasty balloon in a coronary artery. Impedance was calculated when the “balloon” was uninflated (not in contact with the lesion) and inflated (in contact with the lesion). Additionally, different lesion types (Va and Vb, as defined by the American Heart Association) and the effects of the low-conductivity calcium layer were considered. Results showed that the real component of the impedance was much higher when the electrodes were in contact with lesion. Also, when the electrodes were in direct physical contact with the lesion, the difference between various lesion morphologies could be seen by observing the differences in the imaginary and phase component of the impedance. As a consequence of these simulations, it appears plausible that four-point electrodes mounted to an angioplasty balloon may be useful in determining whether a balloon has made contact with a lesion, and in characterizing that lesion.

Keywords—Bioimpedance, finite element, four-point electrode, conductivity, permittivity, atherosclerosis

I. BACKGROUND

ANGIOGRAPHY is a fairly common procedure used in the catheterization laboratory to help locate and characterize atherosclerotic lesions. Intravascular Ultrasound (IVUS) is less common, as well as more costly, but is often necessary to further characterize the lesions. It would be worthwhile to develop a technique that could be used in place of IVUS for a quick estimation of the location, diameter, and composition of the lesion. Konings et al. [1] was able to use a four-point electrode to successfully locate fatty lesions *in vivo* within a coronary artery. We propose that further insight into the composition of the lesion could be gained by measuring the impedance of the lesion using a similar technique.

The proposed electrode would be attached to an angioplasty balloon, which would be inflated to contact the lesion. There are potential difficulties with this technique that need to be addressed to measure the impedance accurately. The environment the electrode would be placed in makes it difficult to characterize impedance. Biological tissue has high ionic conductivity, as well as varying degrees of permittivity at various frequencies. The path the current would take through the volume conductor of the artery would be virtually unknown.

To determine the worth of the proposed technique, we used a finite-element method to calculate the impedance as well as the characteristics of a simulated lesion, such as composition and thickness of the tissue layers. The finite element model (FEM) software package that was used for this simulation was MESH3 (FEM Mesher) and PAC3, and is produced by Field Precision Software.¹

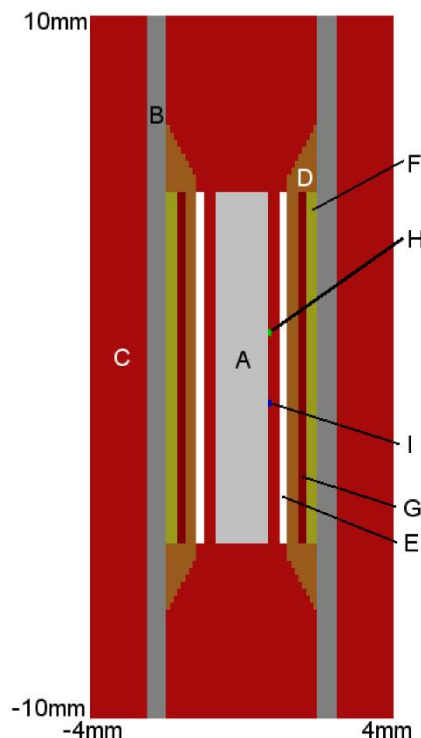


Fig. 1. Generalized cross-sectional geometry of the lesion. (A) catheter balloon (zero conductivity), (B) artery wall, (C) surrounding blood, (D) thrombus, (E) calcium layer, (F) lipid pool, (G) smooth muscle, (H) top electrode, and (I) bottom electrode.

II. GEOMETRY OF LESION

The American Heart Association (AHA) details the progression of atherosclerotic lesions in six stages, type I to type IV.[2] Type I–II lesions occur during the earlier stages of life, and are characterized by fatty streaks consisting of lipid-laden macrophages. As the lesions grow larger, lipid-filled smooth muscle cells accumulate beneath the fatty streaks. Additionally, during the early stages, a slight adaptive thickening occurs in the intima, caused by increased smooth muscle cells surrounded by various amounts of connective tissue. At the very latest stages of type III lesions, there are small pockets of accumulating lipid pools.

As the atherosclerosis develops into types IV–VI, the intimal thickening continues, as more and more muscle cells accumulate. The pockets of lipid pools coalesce into a core of extracellular lipid, and a fibrous plaque starts to form as the lesion progresses from type IV to V. When there is only a thick fibrous cap, it is referred to as a type Va or fibroatheroma. The lesion can progress to a still more complicated state when cal-

¹Field Precision Software, Albuquerque, New Mexico; www.fieldp.com

TABLE I

VALUES FOR THE CONDUCTIVITY AND PERMITTIVITY OF THE TISSUES MODELED FOR THE TYPE Va AND TYPE Vb LESIONS. VALUES IN RED ARE INFERRED.

Material	σ (S/m)			ϵ_r		
	1 kHz	100 kHz	1 MHz	1 kHz	100 kHz	1 MHz
Blood	0.70	0.59	0.80	4000	3000	300
Fat	0.04	0.04	0.04	20000	1000	30
Artery	0.58	0.58	0.58	40000	20000	100
Smooth Muscle	0.50	0.50	0.40	500000	75000	2000
Thrombus	0.24	0.24	0.24	2000	500	10
Calcium	0.08	0.10	0.10	900	400	250

cium starts to form on the surface and the lipid core. It is then referred to as a type Vb lesion. The lesion can also progress to a type Vc lesion, where all or most of the lipid core is absent. The last stage, type VI, involves the formation of fissures, hematoma, and thrombosis, and can be quite unstable.[2], [3], [4]

III. METHODOLOGY

A. FEM Model and Lesion Morphology

Fig. 1 shows an example morphology of a lesion that was modeled using FEM code. Its characteristics are similar to an idealized type Va and type Vb lesions as defined by the AHA. [2] The electrodes were simulated as mounted on a balloon catheter, which was placed proximate to the lesion. The AC voltage on both electrodes was modeled at three different frequencies: 1 kHz, 100 kHz, and 1 MHz. The top electrode was placed at 1 volt and the bottom electrode at -1 volt (or 1 volt at 180° phase). The electrodes were spaced 2 mm apart.

For both type Va and Vb lesions, a simulation was performed for both “high capacitance” and “low capacitance” lesions. The lesion is said to have “low capacitance” when the muscle layer is modeled as 125 μm thick. When the muscle layer is 250 μm thick, it is referred to as “high capacitance”. Values for the conductivity and permittivity (table I) were largely obtained from Gabriel *et al.* [5] and Slager *et al.* [6], though some had to be inferred. The values of the calcified outer layer were inferred from the cancellous bone values. Slager *et al.* measured the conductivity of the thrombus and artery wall for a frequency range of 5 to 500 kHz and obtained a single value. This is reasonable, as most other more thoroughly researched tissues also have relatively constant conductivity values up to about 1 MHz. Consequently, the conductivity values for thrombus and artery were assumed constant up to 1 MHz.

B. Electrode Polarization

The electrodes modeled here consist of two points, with the current flowing from the higher potential point to the lower potential point. Using Ohm’s law, $Z = V/I$, the impedance is determined. For actual *in vivo* measurements, this two-point configuration would be insufficient to measure the impedance accurately. The primary mode of current flow is due to the ionic conductivity of the various tissues. When using a two-

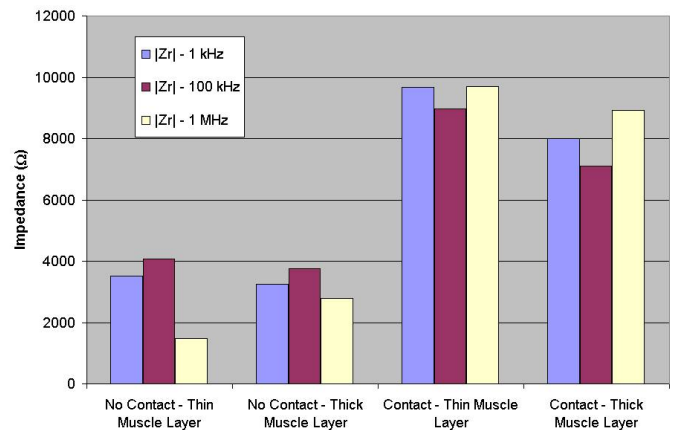


Fig. 2. Measured real impedance for a type Va lesion for uninflated and inflated balloon.

point electrode, a condition called “electrode polarization” occurs.[7] Electrode polarization involves two different current transport mechanisms: faradaic current and capacitive current. The faradaic current is primarily due to the transfer of electrons to the positive ions that exist in the solution. The capacitive current occurs due to the formation of the Helmholtz double-layer: the electric charges due to the ionic content of the solution are distributed across the surface of the electrode, creating a double layer of opposite polarity that acts as a capacitance.[8]

Consequently, if two-point electrodes are used to measure the impedance between the points, they would measure both the impedance due to the properties of the material and the impedance of the electrode–electrolyte interface. To reduce this effect, four-point electrodes would be used for *in vivo* measurements.[9] In order to model this four-point configuration, two electrodes are used, and the electrode impedance is assumed to be negligible. It is also assumed that there is a uniform distribution of specific polarization impedance, such that no net polarization potential exists.[7]

IV. RESULTS

Four different configurations were considered for the simulation. The first two configurations were used to calculate the measured impedance of a type Va lesion prior to contact with the lesion (uninflated balloon) and then in contact with the lesion. The other two configurations consider the same engagement conditions for a type Vb lesion. The essential difference between the two types of lesions is that the type Vb also has a calcified layer approximately 125 μm thick.

Three parameters of the impedance were calculated: the real portion, the imaginary portion and the phase. For both type Va and Vb lesions, the calculated real impedance was much higher when the electrodes were in contact with the lesion than when they were in the blood. Figs. 2 and 3 show the difference between the contact and non-contact configurations. Figs. 4 and 5 show the difference in imaginary impedance between the contact and non-contact configurations. Figs. 6 and 7, display the phase – essentially a ratio between the real and imaginary component of the impedance. Figs. 8, 9, and 10 show the effect of

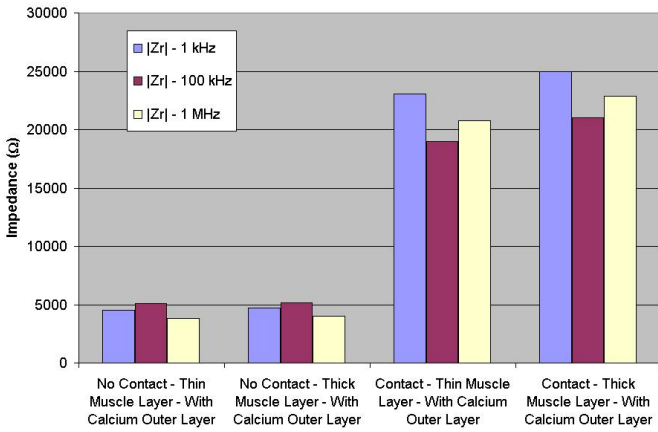


Fig. 3. Measured real impedance for a type Vb lesion for uninflated and inflated balloon.

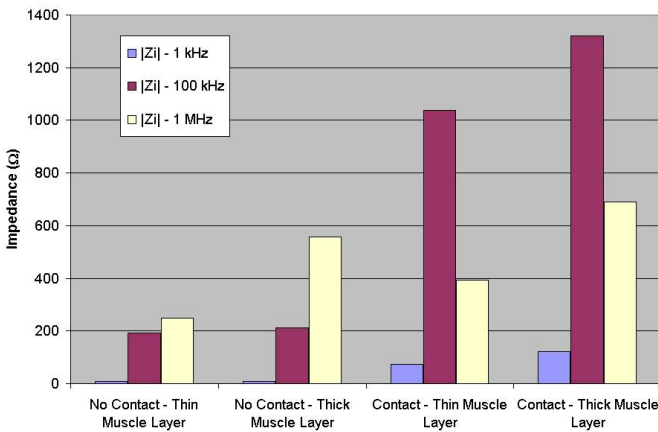


Fig. 4. Measured imaginary impedance for a type Va lesion for uninflated and inflated balloon.

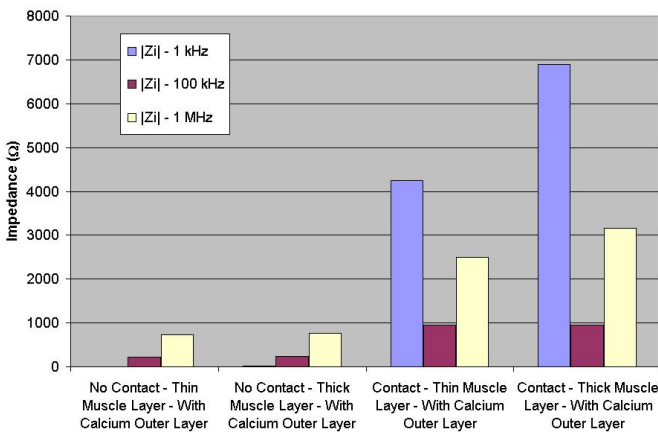


Fig. 5. Measured imaginary impedance for a type Vb lesion for uninflated and inflated balloon.

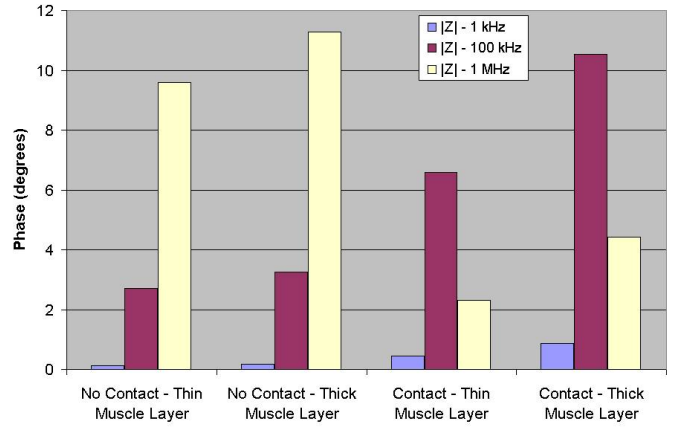


Fig. 6. Measured phase of the impedance for a type Va lesion for uninflated and inflated balloon.

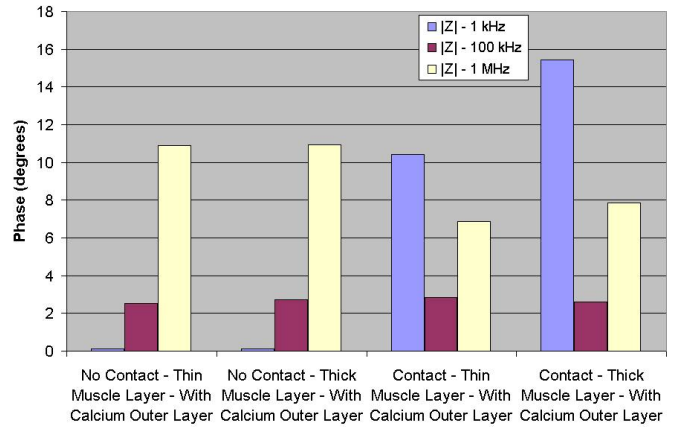


Fig. 7. Measured phase of the impedance for a type Vb lesion for uninflated and inflated balloon.

the highly resistant calcium outer layer plays on the real, imaginary, and phase component of the impedance. Examples of the real portion of the current density in the geometry are shown in figs. 11 and 12. In each case the real portion of the current density is displayed.

V. DISCUSSION

Due to the complexity of actual lesion geometry, the simulated lesion geometry has been somewhat simplified in Fig. 1. In a typical lesion, for example, the layers will not be as uniform as shown. Additionally, there will be fibrous tissue intermingled with the smooth muscle cells. This was essentially modeled in the simulation as a thrombus layer in the outer portion of the lesion. There is also unlikely to be the horizontal and radial symmetry as shown. In fact, the lesion is often eccentric with respect to the lumen.

A. Real portion of the impedance

When observing the results shown in Figs. 2–10, there are noticeable differences between the various configurations. The

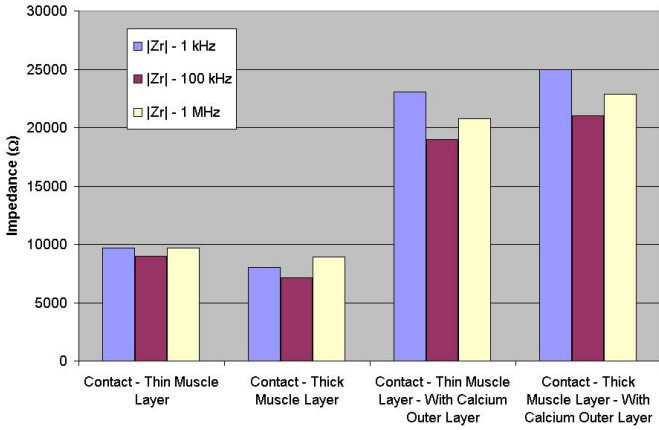


Fig. 8. Comparison of the real impedance for a type Va and type Vb when in contact with the lesion.

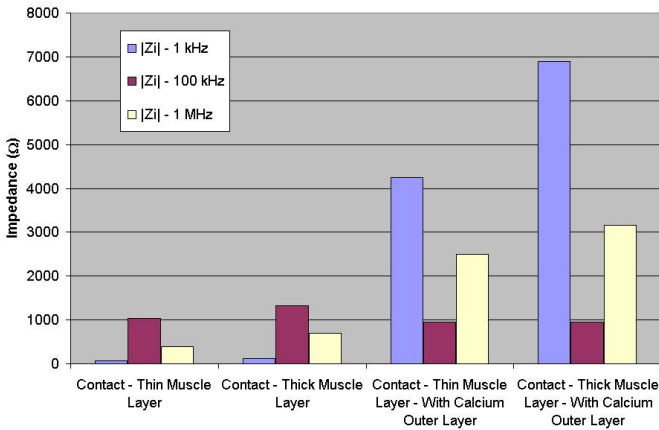


Fig. 9. Comparison of the imaginary impedance for a type Va and type Vb when in contact with the lesion.

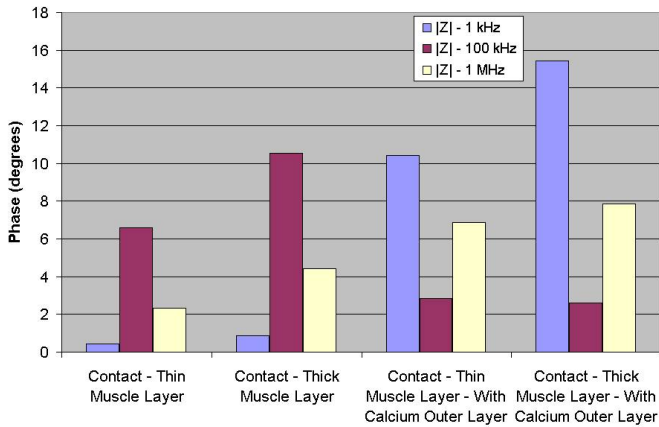


Fig. 10. Comparison of the phase impedance for a type Va and type Vb when in contact with the lesion.

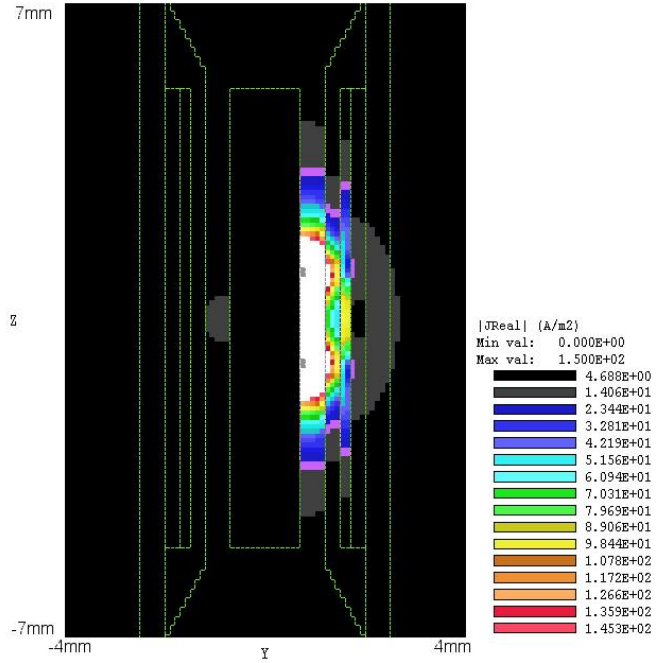


Fig. 11. Real current density before the electrodes engage a smaller lesion. In this instance, the electrodes are only in contact with the blood, which possesses a high conductivity but comparatively low permittivity. The area in white represents real current densities greater than $J = 150 \text{ A/m}^2$. The calculated impedance between the electrodes is $Z = 4073.74 - i192.83$.

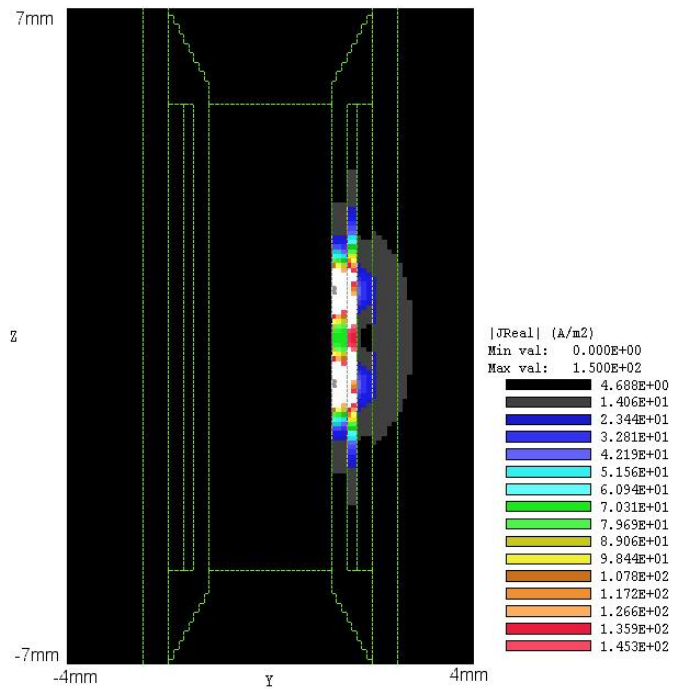


Fig. 12. Real current density after the electrodes engage the smaller lesion. The calculated impedance between the electrodes is $Z = 8979.42 - i1037.37$

most significant difference is that of the real portion of the impedance between the contact and non-contact conditions, for both the types of lesions considered, (Fig. 2 and 3). The conductivity of the blood is much higher than the conductivity of the lesion and artery wall, so this result isn't altogether surprising. In fact, this result shows that it might be easy to determine whether the electrodes have made contact with the lesion geometry *in vivo*. Additionally, due to the low conductivity of the calcium, the measured impedance of the type Vb lesion is much higher than that of the type Va lesion, seen in Fig. 8. This result is significant, as this property may be used to verify the existence of an inelastic calcium layer during an *in vivo* measurement.

B. Imaginary portion of the impedance

The difference in the imaginary component of the impedance between the contact and non-contact conditions are not as striking for the type Va lesion, but the difference between a lesion with a thick muscle layer and a lesion with a thin muscle layer is shown in Fig. 4. If the lesion has a thick muscle layer, the displacement current increases, with a corresponding decrease in the real component of the current. The thick muscle layer causes the imaginary component of the impedance to increase by nearly 30% for all frequency ranges considered. This information obtained may prove valuable, as the capacitance of the lesion, especially at 100 kHz, is determined primarily by the smooth muscle content of the lesion.

In the case where there is a low conductivity layer of calcium on the surface of the lesion, the imaginary component becomes even more important in the determination of the composition of the lesion. For 1 kHz and 1 MHz, there is also a large difference between the imaginary impedance of the high and low capacitance type Vb lesion. In this case, however, the imaginary component does not change much for the 100 kHz condition, as the low real portion of the current dominates. Another noticeable effect of the outer layer of calcium is that it greatly increases the imaginary component of the impedance with respect to the type Va lesion, seen in Fig. 9.

C. Phase of the impedance

The final consideration is that of the ratio of the imaginary to real impedance. This information lies in the phase of the impedance. Fig. 10 reveals that the lesions with thick and thin muscle layers can be differentiated for both the type Va and Vb lesion using the phase information. For the type Va lesion, the phase, in degrees, nearly doubles for a thick muscle layer lesion compared to a thin muscle layer lesion for the frequencies of 100 kHz and 1 MHz. There is a large difference as well for the type Vb lesion, but in this case there is a large change in phase for the frequency of 1 kHz.

D. Surface conductivity

The purpose of this simulation was to estimate the effect various lesion morphologies would have on the measured impedance between two electrodes. One factor not considered, however, is the surface conductivity of the lesion when the balloon is expanded to make contact. The balloon will displace the blood surrounding the lesion almost completely, but there will be a small amount of blood on the surface of the lesion that is not

accounted for in the simulation. For purposes of the simulation, the current going through a film layer of blood was considered to be negligible. It will, nonetheless, likely decrease the difference between the real component of the impedance for the contact and non-contact conditions, and would be a worthwhile topic for future research.

VI. CONCLUSIONS

This purpose of this simulation was to explore the feasibility of mounting a four-point electrode on a balloon catheter and measuring the impedance of various lesions *in vivo*. A large difference in each component of the impedance was found for the various conditions and lesion morphologies. It is believed that this information could be used to help a research or clinical setting differentiate between lesion types and compositions *in vivo*. To further validate this method, a simulation of type IV lesions should be performed. Experimental work to validate these result is planned.

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