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The Impedance of a Spherical Monopolar Electrode

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The impedance of a monopolar electrode immersed in an environmental volume conductor consists of two parts; the impedance of the active electrode-electrolyte interface, and the resistance of the environmental conductor. Two studies were carried out to quantitate these components. First, impedance-frequency data were collected for five spherical stainless-steel electrodes (ranging from 0.473 to 1.11 cm in diameter) immersed in 0.9% saline (ρ = 70 Ω-cm). Impedance measurements were made from 100 Hz to 100 kHz and two sets of data were obtained; one before and one after each electrode was polished with fine emery paper. At low frequency, the measured impedances were high and varied with electrode surface preparation. However, above a transition frequency, the impedances were resistive, independent of the electrode surface preparation, and equal to $\rho/2\pi d$ as predicted from the theory. This study indicates that the low frequency impedance of a monopolar electrode is dominated by the impedance of the electrode-electrolyte interface. Above a transition frequency, the resistance of the environmental conductor dominates, the value of this resistance depending on the electrode geometry and the resistivity (ρ) of the environmental conductor. A second study was conducted, to examine the effect of the distance to the indifferent electrode. A frequency (100 kHz) above the transition frequency was used and impedance data were collected for various distances between the monopolar and indifferent electrodes. The measured resistance increased asymptotically as the distance between the electrodes was increased. When the indifferent electrode diameter was at least 10 times the diameter of the spherical monopolar electrode, the measured resistance was within 5% of the value predicted for an indifferent electrode at infinity.

Keywords*—*Monopolar electrode, Electrode-electrolyte interface, Impedance, Transition frequency.

INTRODUCTION

Electrodes constitute the terminals required for making electrical contact with living tissue. Whereas many types of electrodes exist, they usually fall into two general categories; electrodes for recording bioelectric events and electrodes for stimulating excitable tissue. The former operate at low current density; the latter at high current density. Electrodes are also frequently used for measuring the impedances of biolog-

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ical tissues and fluids, and because biological impedances change with physiologic activity, electrodes may be used to monitor many physiologic events for which no specialized transducers exist. Although a multitude of studies have investigated the properties of electrodes, their behavior is complex and incompletely understood. It was the objective of this study to examine the electrical properties of the spherical monopolar electrode, and the effect of the distance at which the indifferent electrode is located.

A monopolar electrode is defined as a small-area (active) electrode paired with a large-area (indifferent) electrode located at a considerable distance. When it is desired to record biopotentials, stimulate tissue, or measure biological impedances, it is often convenient to use a monopolar electrode. In some applications, where an implanted device is used, the case of the device may serve as the indifferent electrode so that only the active monopolar electrode need be provided. When recording biopotentials, the origin of the bioelectric signal may be located by searching with a monopolar electrode. When a monopolar electrode is used for stimulation, the stimulus is localized to the active electrode where the highest current density exists.

When a monopolar electrode is used for measuring biological impedances, the measured impedance depends on the electrode-electrolyte interface of the monopolar electrode, the geometry of the monopolar electrode, and the resistivity of the environmental conducting medium. It is well-known that the impedance of an electrode-electrolyte interface depends on both frequency and current density with the impedance decreasing as the frequency is increased, or as the current density is increased above the linearity limit (2–7,9–12,15). Because the impedance of an electrode-electrolyte interface decreases with increasing frequency, a transition frequency (f_t) exists, above which the impedance measured with a monopolar electrode is independent of the monopolar electrode-electrolyte interface, and depends only on the geometry of the electrode and the resistivity of the conducting medium. This article examines the frequency and area dependence of the impedance of the spherical monopolar electrode, and demonstrates that when the electrode-electrolyte interface impedance becomes negligible (at frequencies above f_t), the measured impedance is resistive and equal to $\rho/(2\sqrt{\pi A_m}) = \rho/2\pi d$, where A_m is the area, d is the diameter of the spherical monopolar electrode, and ρ is the resistivity of the conducting medium.

THEORY

Consider a spherical monopolar electrode placed in a volume conductor, with the indifferent electrode very large and distant. The impedance measured between these electrodes is the sum of the electrode-electrolyte impedance of the monopolar electrode and the resistance of the environmental volume conductor. It will be shown that with a high-frequency current, the electrode-electrolyte impedance of the monopolar electrode is negligible and the measured impedance is the resistance of the volume conductor.

It is well-known that the resistance of an electrolyte between two concentric spheres is given by

$$R = \frac{\rho}{2\pi}\left(\frac{1}{d_1} - \frac{1}{d_2}\right) , \tag{1}$$

where ρ is the solution resistivity, and d_1 and d_2 are the diameters of the inner and outer spheres, respectively. In the case of a spherical monopolar electrode, the indifferent electrode is very large ($d_2 \gg d_1$) so the resistance of the volume conductor is given by

$$R = \frac{\rho}{2\pi d} = \frac{\rho}{2\sqrt{\pi A_m}} , \tag{2}$$

where d is the diameter and A_m is the area of the monopolar electrode.

Figure 1 illustrates the equivalent circuit for a monopolar electrode immersed an infinite electrolytic volume conductor; R_s and C_s are the series-equivalent resistance and capacitance of the monopolar electrode-electrolyte interface (13,14), and R is the resistance of the volume conductor. The impedance of the large indifferent electrode is negligible with respect to the impedance constituted by R, R_s, and C_s. Therefore, the magnitude of the impedance (Z) measured between the monopolar and indifferent electrodes is

$$Z = \sqrt{(R_s + R)^2 + X_s^2} , \tag{3}$$

where $X_s = 1/2\pi f C_s$ is the reactance of C_s. Both R_s and X_s decrease with increasing frequency, so when the frequency is high enough, the impedance becomes

$$Z = \sqrt{R^2} = R = \frac{\rho}{2\pi d} = \frac{\rho}{2\sqrt{\pi A_m}} . \tag{4}$$

Therefore two regions of the impedance-frequency curve can be identified. Region 1 is the low frequency range where R_s and X_s are greater than R and region 2 is the high frequency range where R_s and X_s are negligible with respect to R. In other words, the electrode-electrolyte impedance is dominant in the low-frequency region 1, and the environmental resistance is dominant in the high-frequency region 2. (Figure 2 illustrates these regions.) Because the electrode impedance varies inversely with

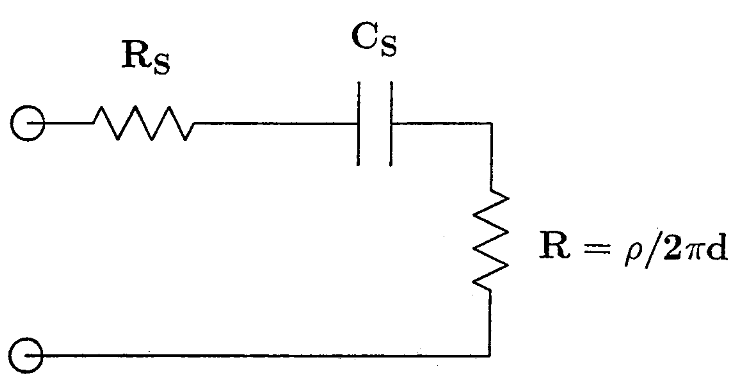


FIGURE 1. Equivalent circuit for a monopolar electrode of diameter *d* immersed in an infinite volume conductor of resistivity ρ; R_s and C_s are the series-equivalent resistance and capacitance of the electrode-electrolyte interface and R is the resistance of the volume conductor.

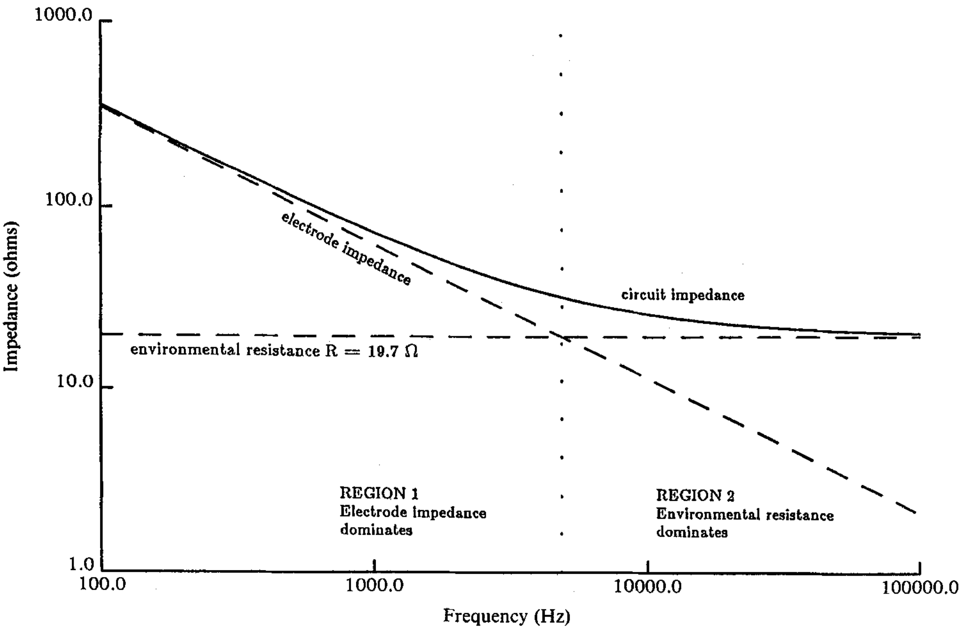


FIGURE 2. The impedance-frequency characteristic of a circuit consisting of a monopolar, spherical, stainless steel electrode, 1 cm^2 in area ($R_S = 4945/f^{0.760}$ and $C_S = 9245/f^{0.734}$) immersed in a volume conductor (ρ = 70 Ω-cm) and paired with a large, distant indifferent electrode. The high-frequency asymptotic impedance is $R = \rho/2\sqrt{\pi A_m}$ = 19.7 Ω.

electrode area, the transition between these two regions will depend on electrode area as well as frequency.

Figure 2 was constructed by using an electrode model (8), in which the series-equivalent resistance and capacitive reactance of an electrode-electrolyte interface, operated at low current density, are given as

$$R_s(\Omega) = (5/S)A/f^{\alpha} \tag{5}$$

and

$$X_s(\Omega) = (5/S)B/f^{\beta} \ , \tag{6}$$

where S is the electrode surface area in cm^2 and A, B, α, and, β are power law factors unique to the given electrode-electrolyte interface. Values for A, B, α, and β have been tabulated in the literature (1,2,8). Substituting Eqs. 4, 5, and 6 into Eq. 3, one obtains the expression used to construct Fig. 2, which represents a spherical monopolar stainless-steel electrode of 1 cm^2 area immersed in saline of resistivity ρ = 70 Ω-cm (A = 989, B = 1849, α = 0.760, and β = 0.734). For this electrode $R = \rho/2\pi\sqrt{A_m}$ = 19.7 Ω, which is the high frequency asymptote shown in Fig. 2.

For practical application of the monopolar electrode, it is important to examine the effect of the distance between the active and indifferent electrodes. The effect of the location of the indifferent electrode may be demonstrated by rewriting Eq. 1

as $R = (\rho/4\pi)(1/r_1 - 1/r_2)$ and plotting the ratio R_X/R_∞ vs. X/r, where r is the radius of the monopolar electrode; X is the radius of the indifferent electrode; R_X is the high-frequency resistance measured between the monopolar and indifferent electrodes, with the indifferent electrode at X; and R_∞ is the high-frequency resistance, which would be measured with the indifferent electrode at infinity. Since $R_X = (\rho/4\pi)(1/r - 1/X)$ and $R_\infty = \rho/4\pi r$,

$$\frac{R_X}{R_\infty} = r\left[\frac{1}{r} - \frac{1}{X}\right] = 1 - \frac{r}{X} = 1 - \frac{1}{n}\,, \tag{7}$$

where $n = X/r$. Figure 3 is a plot of this expression, which shows that the resistance measured between these electrodes increases asymptotically. When $n = X/r > 20$, there is less than a 5% difference between R_X and R_∞, i.e., $R_X/R_\infty > 0.95$.

METHODS AND MATERIALS

Two studied were conducted; the first was designed to demonstrate that the high-frequency impedance of a spherical monopolar electrode is resistive and equal to

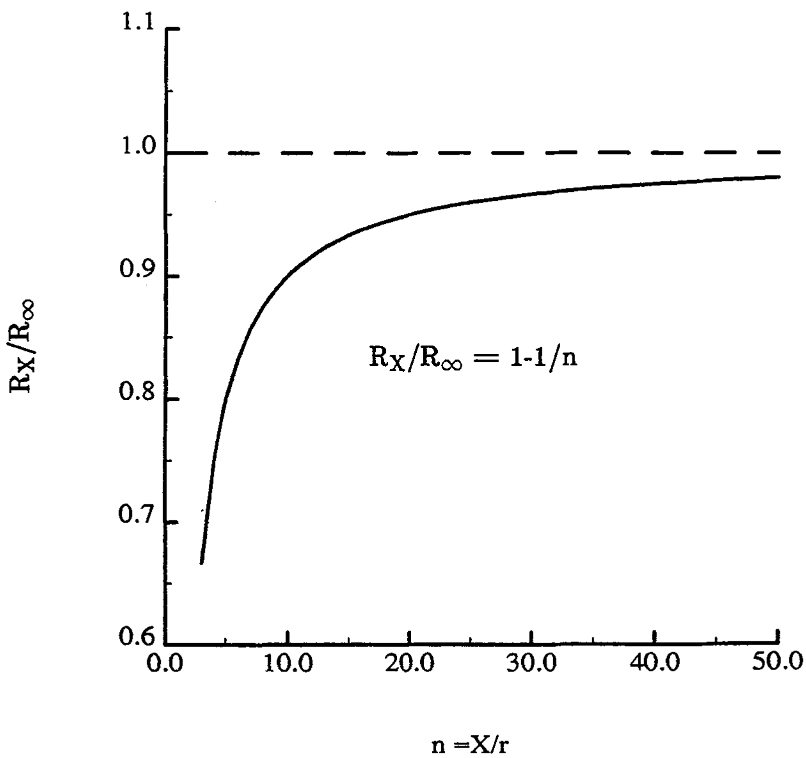


FIGURE 3. The effect of the distance between the monopolar and indifferent electrodes; R_X/R_∞ is the ratio of the resistance measured with the indifferent electrode at X to the resistance which would be measured with the indifferent electrode at infinity and r is the radius of the spherical monopolar electrode.

$\rho/2\pi d$, as well as to examine the frequency at which this occurs for electrodes of different diameters. The second study was designed to examine the importance of the location of the indifferent electrode with respect to the active monopolar electrode. In both studies, 0.9% saline at room temperature (resistivity $\rho = 70\Omega$-cm) was used as the environmental volume conductor.

To demonstrate that the high-frequency impedance is resistive and equal to $\rho/2\pi d$, impedance-frequency data were collected for spherical, stainless steel, monopolar electrodes having diameters d of 0.473, 0.635, 0.794, 0.953, and 1.11 cm. The measurement system is shown in Fig. 4. Each spherical electrode was mounted to the end of a slender wire (approximately 0.84 mm in diameter) which was insulated with thin-walled Teflon tubing (approximately 0.25 mm wall thickness). The indifferent electrode was made of 0.10 mm thick brass which was coiled to form a cylinder. In all cases the area of the indifferent electrode was more than 350 times the area of the spherical monopolar electrode and the volume conductor extended to well beyond 20d in all directions. A function generator (Model 166, Wavetek, San Deigo, CA) provided a sinusoidal voltage that was stepped up through a 1:50 transformer which also provided isolation. A 20 kΩ damping resistor was placed across the secondary of the transformer and two 20 kΩ current-limiting resistors were placed in series with the monopolar and indifferent electrodes as shown in Fig. 4. For each of the five spherical electrodes, the current required to establish a 0.05 mA/cm^2 peak-to-peak current density was set by adjusting the voltage V_I across one of the 20 kΩ current-limiting resistors. The 0.05 mA/cm^2 current density was selected because it provided adequate signal-to-noise ratio, while staying well below the current density linearity limit for stainless steel (2,7). The voltage V between the monopolar and indifferent electrodes was measured at frequencies of 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, and 100000 Hz, and the corresponding impedances were calculated as $Z = V/I = (20\ \mathrm{k}\Omega) V/V_I$. The peak-to-peak voltages V and V_I were measured with a dual-trace oscilloscope (Model 5111A, Tektronix, Beaverton OR). Two sets of impedance-frequency data were obtained for each spherical electrode; one before and one after each electrode was polished with fine (number 600) emery paper.

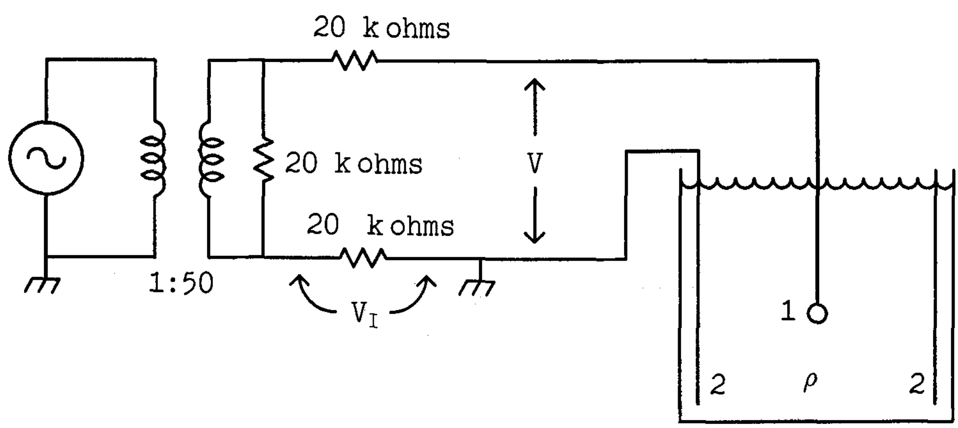


FIGURE 4. Circuit used to measure the impedance between a spherical monopolar electrode, 1, and a large, cylindrical indifferent electrode, 2, both of which are immersed in a volume conductor of resistivity ρ.

To examine the effect of the location of the indifferent electrode, tests were conducted on the smallest (0.473 cm diameter) and largest (1.11 cm diameter) stainless steel spherical electrodes. The electrodes were immersed in a 0.9% saline volume conductor which extended to well beyond $20d$ in all directions. The indifferent electrode again consisted of 0.10 mm thick brass which was coiled to form cylinders of different diameters, providing ratios of X/r from 2 to at least 20. For each value of X/r, the high-frequency (100 kHz) impedance between the monopolar and indifferent electrodes was measured. It will be shown that at 100 kHz, the impedance of these spherical electrodes is negligible and the measured impedance is the resistance of the volume conductor. Recall that R_X is the resistance measured with the indifferent electrode at X, R_∞ is the resistance which would be measured with the indifferent electrode at infinity, and r is the radius of the spherical monopolar electrode. For each ratio of X/r, the ratio of R_X/R_∞ was calculated. Because it is not possible to place an indifferent electrode at infinity, the value of R_X measured at the largest ratio of X/r (39 for the small spherical electrode and 22 for the large spherical electrode) was used to approximate R_∞.

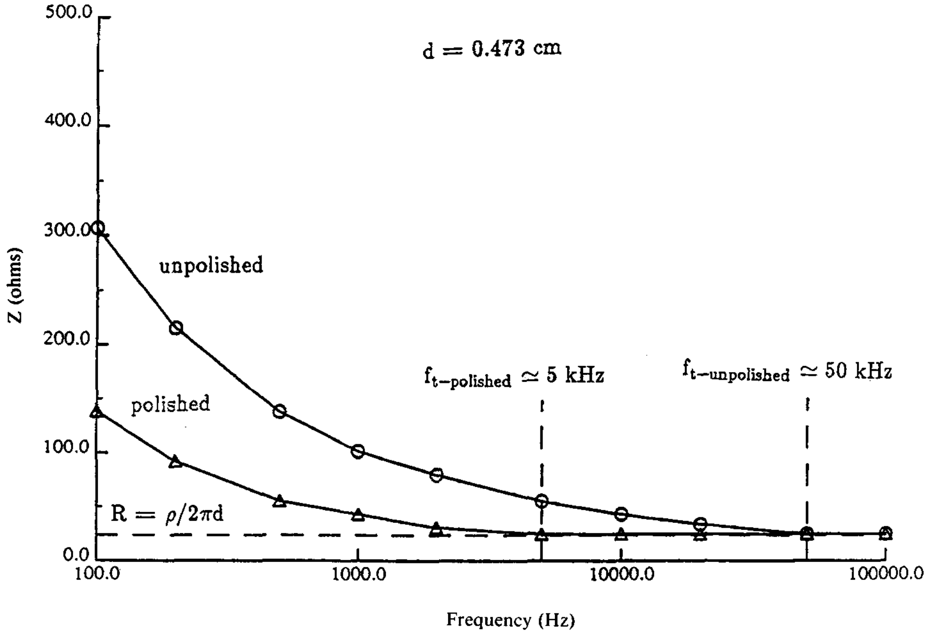
RESULTS

Figure 5 presents the impedance (Z) measured between the active and indifferent electrodes plotted vs. frequency for the smallest ($d = 0.437$ cm) and largest ($d = 1.11$ cm) spherical monopolar electrodes studied. Each plot represents one electrode and each contains two curves, one for the unpolished and one for the polished electrode. The theoretical value of the high-frequency impedance ($Z = R_\infty = \rho/2\pi d$) is shown on each plot. In addition, the transition frequency (f_t), defined as the frequency at which Z comes within 5% of $\rho/2\pi d$, is identified for each curve. Table 1 summarizes the results for all of the electrodes studied. The values of R_∞ are presented as are the values of f_t for both unpolished and polished electrodes.

In all cases, the measured impedance decreased with increasing electrode area and increasing frequency. At frequencies above f_t, the phase angle was less than 5° indicating that the high-frequency impedance was essentially resistive. Furthermore, polishing the electrodes with fine emery paper reduced the transition frequency (f_t) in all cases. At low frequency (below f_t), the unpolished-electrode impedance was higher than the polished-electrode impedance for all of the electrodes studied. However, above the transition frequency (f_t), there was less than 5% difference between the impedances of the unpolished and polished electrodes.

TABLE 1. Transition frequencies (f_t) and high frequency asymptotic impedance values ($R_\infty = \rho/2\pi d$) for five spherical stainless steel monopolar electrodes immersed in 0.9% saline at room temperature ($\rho = 70$ Ω-cm).

Electrode Diameter d (cm)	f_t (kHz) for Unpolished Electrode	f_t (kHz) for Polished Electrode	$R_\infty = \rho/2\pi d$ (ohms)
0.473	50	5	23.6
0.635	50	5	17.5
0.794	50	10	14.0
0.953	20	2	11.7
1.11	10	5	10.0



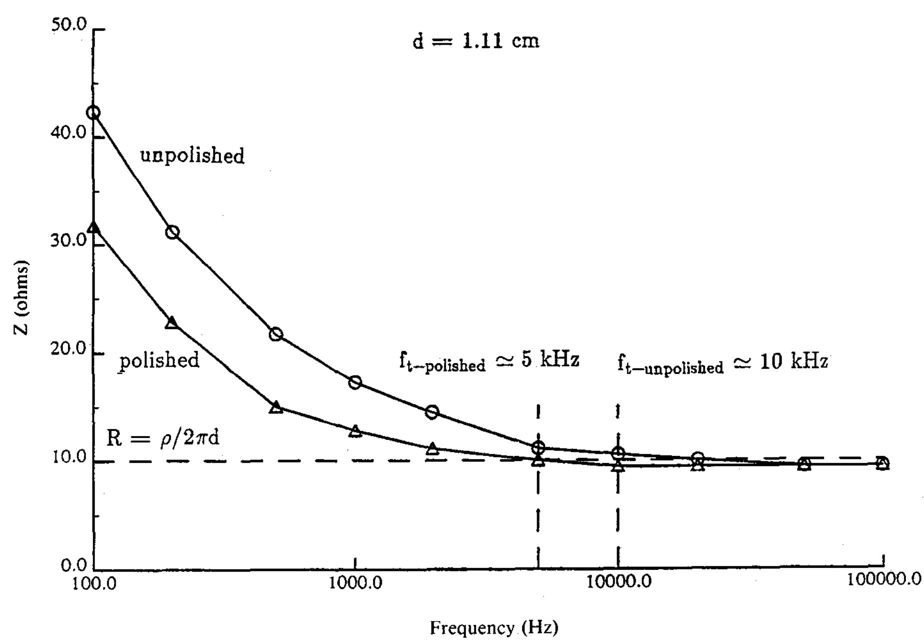


FIGURE 5. Impedance (Z) vs. frequency for 0.473 and 1.11 cm diameter spherical, stainless-steel monopolar electrodes immersed in 0.9% saline (ρ = 70 Ω-cm). The dashed horizontal lines indicate the high-frequency asymptotic impedance ($R = \rho/2\pi d$) and the dashed vertical lines indicate the transition frequency (f_t = the frequency at which the measured impedance comes within 5% of $\rho/2\pi d$).

For the 0.473 cm, 0.635 cm, and 0.794 cm diameter unpolished spherical electrodes, Z came within 5% of $\rho/2\pi d$ when the frequency was 50 kHz, i.e., $f_t = 50$ kHz. The transition frequency was lower for the largest two unpolished electrodes; 20 kHz for the 0.953 cm diameter electrode and 10 kHz for the 1.11 cm diameter electrode. For the polished electrodes f_t was between 2 kHz and 10 kHz. The polished electrodes exhibited no clear decrease in f_t with increasing electrode area.

The effect of the location of the indifferent electrode is shown in Fig. 6, which is a plot of the ratio R_X/R_∞ vs. X/r for the smallest (0.473 cm diameter) and largest (1.11 cm diameter) spherical electrodes studied. The ratio R_X/R_∞ increased asymptotically as the ratio X/r was increased and when $X/r > 15$, $R_X/R_\infty > 0.95$.

DISCUSSION AND CONCLUSIONS

The two regions of the impedance-frequency curve (the low frequency region in which the electrode-electrolyte impedance of the spherical monopolar electrode dominates the system, and the high-frequency region in which the resistance of the environmental volume conductor dominates the system), as well as the transition frequency (f_t), were identified for each of the five spherical monopolar electrodes stud-

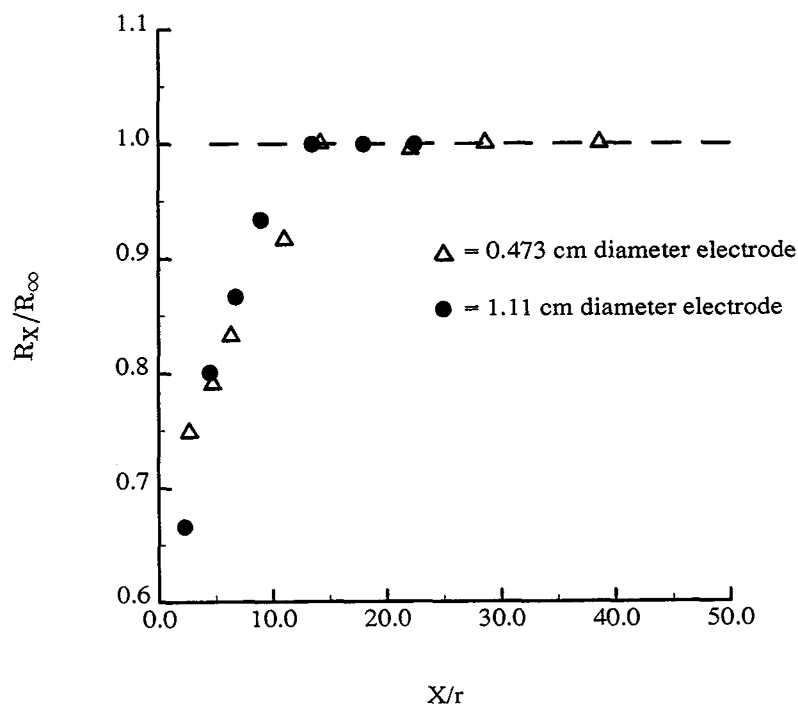


FIGURE 6. The effect of the distance between the monopolar and indifferent electrodes; R_X/R_∞ is the ratio of the resistance measured with the indifferent electrode at X to the resistance which would be measured with the indifferent electrode at infinity. Because it is not possible to place an indifferent electrode at infinity, the value of R_X at the largest ratio of X/r was used to approximate R_∞.

ied. In all cases, the high-frequency impedance was resistive and within 5% of the theoretical value ($R = \rho/2\pi d$) for a spherical monopolar electrode.

Polishing a stainless-steel electrode removes surface contaminants such as oxides. Therefore, it is not surprising that, in the low frequency region, the polished electrodes exhibited lower impedances than the unpolished electrodes. The fact that there was very little difference between the unpolished and polished electrode impedances at high frequency emphasizes the point that the high-frequency impedance is relatively independent of the electrode-electrolyte interface, and is determined primarily by the geometry of the electrode and the resistivity of the environmental conductor. Because the transition frequency represents the frequency at which the electrode-electrolyte impedance becomes negligible, with respect to the resistance of the environmental volume conductor, f_t will be lower for the polished electrodes than for the unpolished electrodes.

Studies on the effect of the location of the indifferent electrode indicate that as the distance between the spherical monopolar and indifferent electrodes is increased, the impedance measured between these electrodes increases asymptotically. Theory (Fig. 3) indicates that when the radius of the indifferent electrode is 20 times the radius of the monopolar electrode, the measured impedance is within 5% of the value predicted for an indifferent electrode at infinity. That is, when $X/r \geq 20$, $R_X/R_\infty \geq 0.95$. The data (Fig. 6) suggest that a slightly smaller value of $X/r > 15$ may be adequate to achieve $R_X/R_\infty > 0.95$. This discrepancy is probably due to experimental overestimation of the ratio R_X/R_∞. First, because it is not possible to construct a real system with an indifferent electrode at infinity, R_∞ is underestimated and hence R_X/R_∞ is overestimated in any real system. Furthermore, the data represent a system with a cylindrical rather that a spherical indifferent electrode, and this may contribute to overestimation of R_X/R_∞.

In conclusion, we have shown that, above a transition frequency (f_t), the impedance of a spherical monopolar electrode of diameter d, immersed in a volume conductor of resistivity ρ, is resistive and equal to $\rho/2\pi d$. We have also shown that, when the indifferent electrode is more than $10d$ distant from the active electrode, the measured resistance is essentially that which would be measured with the indifferent electrode at infinity.

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NOMENCLATURE

A = species specific constant in resistance vs. frequency power-law
A_m = monopolar electrode surface area (cm^2)
α = species specific exponent in resistance vs. frequency power-law
B = species specific constant in capacitive reactance vs. frequency power-law
β = species specific exponent in capacitive reactance vs. frequency power-law
C_s = series-equivalent electrode-electrolyte capacitance (microfarads)
d = monopolar electrode diameter (cm)
f = frequency (Hz)
f_t = transition frequency (Hz)
n = X/r = ratio of indifferent electrode radius to monopolar electrode radius
Ω = ohms
r = monopolar electrode radius (cm)
R = resistance (ohms)
R_s = series-equivalent electrode-electrolyte resistance (ohms)
R_X = electrolytic resistance between monopolar and indifferent electrodes with indifferent electrode at X (ohms)
R_∞ = electrolytic resistance between monopolar and indifferent electrodes with indifferent electrode at infinity (ohms)
ρ = resistivity (ohm-cm)
S = electrode surface area (cm^2)
μF = microfarads
V = voltage between monopolar and indifferent electrodes
V_I = voltage across current-limiting resistor
X = indifferent electrode diameter
X_S = reactance of series-equivalent capacitance (ohms)
Z = impedance (ohms)
∞ = infinity