5.1 The reaction

$$\text{Ag} \rightarrow \text{Ag}^{+} + e^{-} \qquad \text{(P 5.1.1)}$$

gives one silver ion per electron. By definition, a current of 10 μA is equivalent to

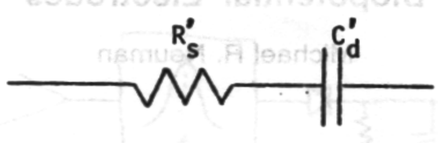
$$10\ \mu\text{A} = 10^{-5}\ \text{C/s} \qquad \text{(P 5.1.2)}$$

The charge on the electron is 1.6×10^{-19} C. Thus the number of silver ions oxidized at the electrode-electrolyte interface per second will be

$$N = \frac{10^{-5}}{1.6 \times 10^{-19}} = 6.25 \times 10^{13} s^{-1} \qquad \text{(P 5.1.3)}$$

5.4 **The equivalent circuit model of an electrode with electrolyte gel coupling it to the skin is that shown in Fig. 5.4. When the electrode is wetted by the electrolyte gel, R_s and R_d will have their minimal value since there will be a large surface area coupling the electrode to the skin. R_s will be at its minimal value because the electrolyte at the interface, consisting primarily of the gel, will be a relatively good conductor. C_d will have its greatest value since the area of contact between the electrode and the electrolyte will be large. As the electrolyte gel begins to dry, R_s will increase as the effective conductance of the electrolyte decreases as a result of decreasing contact area with the electrolytic solution. There will also be a decrease in conductivity of the electrolytic solution resulting from lower effective ion mobility due to increased concentration and salt precipitation. R_d will increase and C_d will decrease because of the decrease in effective electrode contact area. When completely dry R_d will be infinite or nearly infinite and C_d will be quite small.**

Under these circumstances, the equivalent circuit will reduce to a series combination of the new R_s and the new C_d denoted by primes as indicated below. Note that there is no longer any electrode-electrolytic solution interface to produce it. The ECG will lose its low-frequency components because C_d' and the amplifier input impedance act as a high-pass filter.



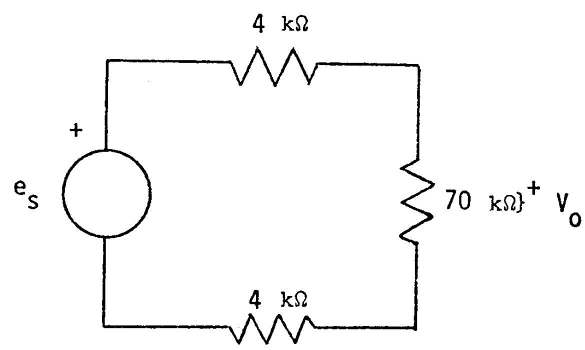
5.5 There will be a potential difference between the electrodes due to the difference in half-cell potentials for the two materials. These potentials and the associated reactions are taken from Table 5.1 and are given below:

$$Zn \rightarrow Zn^{2+} + 2e^- \qquad -0.763\ V \qquad (P\ 5.5.1)$$

$$Al \rightarrow Al^{3+} + 3e^- \qquad -1.706\ V \qquad (P.5.5.2)$$

The voltage difference between these two reactions is 0.943 V with the Al being negative, thus this potential will appear between the two wires.

5.10 The equivalent circuit for this situation is shown below.



The output voltage is given by the voltage divider equation

$$V_0 = \frac{70k}{70k + 4k + 4k} e_s = 0.897\ e_s \qquad (P\ 5.10.1)$$

5.11 By cleaning the silver-silver chloride electrode with steel wool, some of the silver chloride layer will no doubt be scratched off exposing elemental silver. The half-cell potential for silver is different from that of silver chloride as noted in Table 5.1 and elemental silver is more polarizable than the silver salt. Thus, the effects associated with polarization, namely increased motion artifact, noise, and low-frequency source impedance, should increase following the steel wool cleaning. In addition, the half-cell potential of the electrode will be different after the cleaning procedure. All of this acts together to give an electrode which will be more unstable and not as good for cardiac monitoring.

5.12 (a) The resistance of the metal tip of the electrode can be determined approximately from geometric considerations and the resistivity of the metal.

$$R = \rho \frac{L}{A} = 1.2 \times 10^{-5}\ \Omega \bullet cm \frac{3mm}{(1\mu m)^2 \pi/4} = 458\Omega \qquad (P\ 5.12.1)$$

(b) Only the cross-section of the microelectrode tip will contact the electrolytic solution within the cell (cytosol). This surface area is

$$A = \frac{(1\mu m)^2 \pi}{4} = 7.85 \times 10^{-9}\ cm^2 \qquad (P\ 5.12.2)$$

The conductance of the interface will be given by the conductance per square centimeter of interface multiplied by the cross-sectional area of the tip

$$G = 7.85 \times 10^{-9}\,\text{cm}^2 \times 10^{-3}\,\text{S/cm}^2 = 7.85 \times 10^{-12}\,\text{S} \qquad \text{(P 5.12.3)}$$

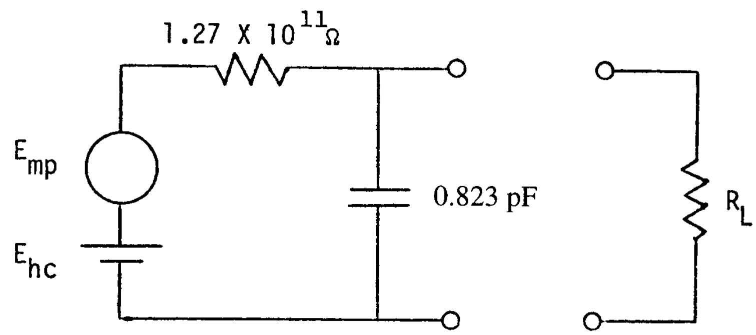
which is equivalent to a resistance of $1.27 \times 10^{11}\ \Omega$. Clearly this is the dominant resistance for the microelectrode and the resistance due to the metal tip as calculated in part (a) is insignificant when compared to this value.

(c) The capacitance associated with the tip of this microelectrode can be calculated using Equation 5.16.

$$C = \frac{2\pi \times 1.67 \times 8.8 \times 10^{-12} \times 3 \times 10^{-3}}{\ln (1.4/1)}$$

$$= 0.823\ \text{pF} \qquad \text{(P 5.12.4)}$$

(d)



(e) Connecting the electrode to the amplifier places resistance R_L, shown in the figure above, across the capacitor. The ac Thevenin equivalent resistance of the electrode-amplifier combination seen from the terminals of the capacitor will then be the parallel combination of R_L and the source resistance of the electrode. Since R_L is several orders of magnitude lower than the source resistance, the Thevenin equivalent will equal approximately the resistance R_L. Thus, the circuit becomes a low-pass filter having a corner frequency given by

$$f = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 10^7\ \Omega \times 0.823\ \text{pF}}$$

$$= 1.92 \times 10^4\ \text{Hz} \qquad \text{(P 5.12.5)}$$

When the input impedance of the amplifier is increased to 100 MΩ the corner frequency will be one-tenth of the above value. It is seen that the increase in input impedance of the amplifier from 10 MΩ to 100 MΩ has reduced the high corner frequency of the low-pass filter to below 2000 Hz. At these frequencies, one begins to get significant distortion of depolarization and repolarization waveforms themselves, primarily present in the form of diminished rise times. Nevertheless, since the input impedance of the amplifier is much lower than the source impedance of the electrode, one does get a tenfold increase in signal amplitude from this modification. For intracellular biologic applications, it would be more desirable to use an amplifier with much higher input impedance and a negative capacitance input characteristic to both increase signal amplitude and minimize loading of the microelectrode as well as to extend the effective frequency response of the system.