Measuring Skin Impedance Using an LCR Databridge: What Frequency Should be Used?

Erick A. White and Annette L. Bunge

Colorado School of Mines, Golden, Colorado, USA

Introduction

- Impedance measurements:
  - Are the alternating current (AC) analog to the direct current (DC) resistance (i.e., equal to the ratio of potential to current)
  - Vary with the frequency of the applied current or potential because skin contains elements that behave like capacitors as well as resistors
- Skin impedance measurements for integrity testing:
  - Are fast, relatively economical and non-invasive
  - Are sometimes determined using an LCR databridge (for example, from PRISM or Tinsley) at either 100 Hz or 1000 Hz; these are reported as "resistances" in either the PAR or SER mode (i.e., R_{PAR} and R_{SER}, respectively)
- Minimum "resistance" values for acceptable skin integrity have been proposed based on LCR databridge measurements in PAR mode:
  - 25 kΩ·cm² based on R_{PAR} measured at 100 Hz [1]
  - 11 kΩ·cm² based on R_{PAR} measured at 1000 Hz [2]

Low Skin Resistivity Indicates Damaged Skin

- Damaged skin has a reduced barrier to ionic transfer
- Electrical resistivity (ρ) characterizes the skin barrier to ionic transfer
  - Because the skin barrier thickness (ℓ) is not always known, it is more convenient to report the product of resistivity and the skin barrier thickness; i.e., $\rho\cdot\ell$
  - But $\rho\cdot\ell$ is equivalent to the product of the DC skin resistance (R_{skin}) and the skin area (A); that is, $\rho\cdot\ell = R_{skin}\cdot A$, which has units of Ohms-cm² (or Ω-cm²)
  - Low values in the skin resistivity (i.e., $R_{skin}\cdot A$) are consistent with damaged skin
- Permeability of a polar chemical across skin is proportional to $1/(R_{skin}\cdot A)$ [3]

What Do R_{PAR} and R_{SER} Measurements Represent?

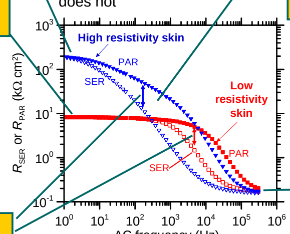
- AC measurements of the ratio of potential (V) and current (I) consist of *real* and *imaginary* components
- Thus, impedance (Z), which is the ratio of potential (V) to current (I), has real (Z_r) and imaginary (Z_j) components:
  - That is, $Z = Z_r + iZ_j$ where $i = \sqrt{-1}$
  - LCR databridge "resistance" values reported in SER mode (R_{SER}) are equal to the real component of the impedance value: $R_{SER} = Z_r$
- Admittance (Y) is the ratio of current (I) to the potential (V): $Y = I/V = 1/Z$; admittance is the AC analog to DC measurements of conductance
  - Admittance has real (Y_r) and imaginary (Y_j) parts: $Y = Y_r + iY_j$
  - LCR databridge "resistance" values reported in PAR mode (R_{PAR}) are equal to the real component of the inverse of the admittance values: $R_{PAR} = 1/Y_r$
- While $Z = 1/Y$, $Z_r \neq 1/Y_r$ unless $Z_j = Y_j = 0$; therefore, R_{SER} and R_{PAR} for skin are usually different except at low and high frequency
- R_{SER} and R_{PAR} both vary with frequency; neither R_{SER} nor R_{PAR} represent R_{skin} except when the electrolyte resistance (R_{elec}) and frequency are both small
- See figure below showing the variation of R_{SER} and R_{PAR} with frequency for skin samples with high and low resistivity (experimental method described on the right)

Comparing R_{PAR} and R_{SER} measured as a function of frequency for two skin samples

At low values of frequency, R_{SER} and R_{PAR} are both equal to the sum of the DC resistances of skin plus the electrolyte solution (R_{skin} + R_{elec})

The high resistivity skin sample has acceptable integrity, while the low resistivity skin sample does not

At intermediate values of frequency, R_{SER} and R_{PAR} both decrease with increasing measurement frequency



At the same value of an intermediate frequency value, R_{PAR} > R_{SER} for a given skin sample

At high values of frequency, R_{SER} and R_{PAR} are both equal to the DC resistance of the electrolyte solution (R_{elec})

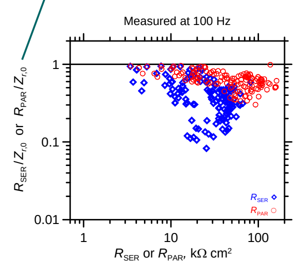
Does R_{SER} or R_{PAR} Measured at 100 or 1000 Hz Using an LCR Databridge Equal R?

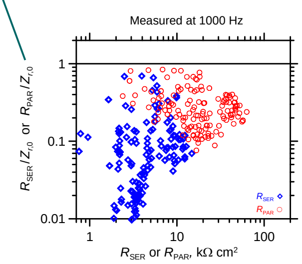
- Impedance and admittance measurements at 100 Hz and 1000 Hz were examined to assess how well R_{PAR} and R_{SER} determined at 100 Hz and 1000 Hz estimate the low frequency real component of impedance $Z_{r,0}$, which is approximately the DC resistance of the skin plus the electrolyte solution (R); experimental methods are described below the figure.
- Measured values of R_{PAR} and R_{SER} are compared to $Z_{r,0} \approx R$ for 149 pieces of human cadaver skin from 6 different subjects (see below)

Comparing R_{SER} and R_{PAR} measured at 100 and 1000 Hz to the DC resistance $R = R_{skin} + R_{elec}$

This ratio is 1 if the measured R_{SER} or R_{PAR} is equal to the low frequency real component of impedance ($Z_{r,0}$), which is approximately equal to the DC resistance of the skin and electrolyte ($R = R_{skin} + R_{elec}$)

- This ratio is closest to 1 when measured at 100 and reported in PAR mode
- Measurements at 1000 Hz can underrepresent the DC resistance by 10-fold when reported in PAR mode and by 100-fold when reported in SER mode





Ratio is plotted as a function of the measured R_{SER} or R_{PAR}.

- Measurements at 1000 Hz are smaller than measurements at 100 Hz
- When measured at the same frequency, $R_{SER} \leq R_{PAR}$

Experimental Methods

Impedance was measured at 32°C in side-by-side diffusion cells filled with 0.01 M phosphate buffered saline (PBS) after the skin had equilibrated

- Impedance spectra were determined (Gamry Potentiostat, model PCI4/300, with four Ag/AgCl electrodes) from the current response to a small amplitude sinusoidal potential (10 mV root mean squared), which minimized skin damage and confined the scan to the pseudo-linear region of the current versus voltage curve
- The measured frequency range was at least 1 Hz to 10 kHz with 10 measurement points per logarithmic decade

Conclusions

- Skin resistivity (and skin integrity as indicated by the barrier function to ions) is represented better by:
  - Impedance measured at 100 Hz than 1000 Hz
  - Databridge "resistance" measurements reported as R_{PAR} rather than R_{SER}
- Impedance measured at less than 100 Hz will represent skin resistivity (and skin integrity) even better, although experimental artifacts may arise for measurements at less than 10 Hz
- Resistance measurements reported by a Tinsley-type LCR databridge:
  - Do not represent the DC resistance R
  - Are equal to the real component of the impedance when reported as R_{SER} and the inverse of the real component of the admittance when reported as R_{PAR}

Acknowledgments

Mark E. Orazem, Department of Chemical Engineering, University of Florida, Gainesville

US National Institute of Occupational Safety and Health (NIOSH). No endorsement from NIOSH or the US government should be inferred.

References Cited

1. Davies DJ, Ward RJ, Heylings JR. Multi-species assessment of electrical resistance as a skin integrity marker for in vitro percutaneous absorption studies, Toxicol In Vitro, 18:351-358 (2004).
2. Fasano WJ, Manning LA, Green JW. Rapid integrity assessment of rat and human epidermal membranes for in vitro dermal regulatory testing: correlation of electrical resistance with tritiated water permeability, Toxicol In Vitro, 16:731-740 (2002).
3. Peck KD, Ghanem AH, Higuchi WI. Hindered diffusion of polar molecules through and effective pore radii estimates of intact and ethanol treated human epidermal membrane. Pharm Res, 11:1306-1314 (1994).