
Electrical Modeling of Membrane Hydration and Movement of Protective Gloves in Conductive Solution

SHENGKE ZENG, PH.D.

National Research Council Research Associate, Division of Safety Research, National Institute for Occupational Safety and Health, Morgantown, West Virginia

RICHARD B. BEARD, PH.D.

Lester Kraus Professor of Electrical and Computer Engineering, Biomedical Engineering and Science Institute, Drexel University, Philadelphia, Pennsylvania

STEPHEN P. BERARDINELLI, PH.D.

Scientist Officer, Acting Chief of Protective Equipment Section, Division of Safety Research, National Institute for Occupational Safety and Health, Morgantown, West Virginia

An electrical circuit model of protective barrier membranes used to isolate a glove wearer from a surrounding conductive solution has been developed as a 12-loop equivalent circuit. The total effective parallel conductance (G) and capacitance (C) of a latex or nitrile glove, donned and then immersed in a conductive solution or body fluid is represented by 22 conductance-capacitance elements. This circuit simulates the frequency dependency of the G and C , and the nonlinear relationships between G and C and membrane interfacial area. Results from this circuit model illustrate that the frequency dependency is attributable to the multiple-impedance layers formed by glove membrane hydration, and the nonlinear relationships of the G and C to interfacial area caused by the wet outer glove membrane surface. The frequency dependency and the nonlinear relationships seriously affect the accuracy and sensitivity of electrical glove testers using the G , conductance rate dG/dt , or quality factor Q as the penetration indicator. Some necessary considerations for the designs of these three types of glove testers are suggested.

Index under: Conductance, Electrical; Capacitance, Electrical; Latex Gloves, Testing; Nitrile Gloves, Testing; Testing, Latex or Nitrile Gloves; Model, Gloves; Equivalent Circuit, Gloves.

INTRODUCTION

The protective barrier afforded by surgical latex gloves, and similar gloves composed of nitrile and related substances, frequently provides healthcare workers with their only protection against direct contact between the skin and patients' bodily fluids that can contain pathogenic agents. OSHA standards, as established in the *Bloodborne Pathogens Rule*, and common infection control practices mandate the use of gloves as an item of personal protective clothing (OSHA, 1991). These barriers may be defective because of various holes that are formed, either during manufacturing or during use. Various electrical methods are currently used to test the integrity of the protective gloves before use or during operative procedures (Albin, 1992; Stampfer, 1994). They include electrical conductance level test (Albin, 1990; Beck, 1961; Leach, 1993; Langdon, 1990), a test

for the rate change of the electrical conductance level (Williams, 1992; Cox, 1994), and an electrical quality factor test (Beard, 1993). These test methods monitor the glove penetration indicators, such as the conductance of a glove, the conductance-variation rate of a glove, or the quality factor of a glove, in conductive solution such as a patient's body fluid. A higher conductance or conductance-variation rate, or a lower quality-factor value indicates the penetration or defect of a protective glove, and a specific alarm would be activated. In practical uses, these electrical glove testers encounter some problems such as glove membrane hydration, which causes a conductance and capacitance shift. In addition, glove position variation can produce a steep change in glove conductance and capacitance. These changes in conductance and capacitance can cause false alarms and lower

the penetration detection sensitivity. It is necessary to develop a general electrical circuit model of a protective glove in a conductive solution in order to analyze the effects of glove-membrane hydration and glove position variation on the accuracy and sensitivity of electrical glove testers.

Beard and colleagues used a simplified protective glove model to analyze the quality factor of a protective glove or a condom in a conductive solution (Beard, 1993). The electrical circuit model contains a parallel membrane conductance and a parallel membrane capacitance, as shown in Figure 1(a). The penetration-caused decrement in the quality factor of a glove was successfully simulated. This simplified glove model, however, cannot explain two phenomena discovered in glove conductance and capacitance measurements: the frequency dependency of the total effective parallel glove conductance (G) and the total effective parallel glove capacitance (C), and the nonlinear relationships of the G and C to membrane interfacial area. Here the membrane interfacial area is the part of the outer glove membrane area that contacts a conductive solution. The frequency dependency can be observed as the G and C of a protective glove are measured while the glove is immersed in an arbitrarily fixed depth of conductive solution with variation in the applied measurement frequency. The G increases and the C decreases with the ascending measuring frequency, and vice versa. The nonlinear relationships can be observed as the G and C of a protective glove are measured with a wet outer membrane and with variation in glove interfacial area at an arbitrarily fixed measuring frequency ranging from 100 Hz to 1 MHz. The experimental results show that the G and C are not simple linear functions of the interfacial area. The G may be directly related or

even inversely related to the interfacial area, depending upon the measuring frequency and the glove position in the solution. In other words, the measured G may have a maximum when a protective glove moves in a conductive solution at certain fixed frequencies. Publications and patents on electrical glove testers have not addressed the above phenomena, which could seriously question the accuracy and sensitivity of electrical glove testers (Albin, 1992, 1990; Beard, 1993; Beck, 1961; Cox, 1994; Langdon, 1990; Leach, 1993; Stampfer, 1994; Williams, 1992). The development of a more realistic electrical model is needed in order to explore the mechanisms of these phenomena, and to provide general guidance for the design of next-generation electrical glove testers.

In order to account for the electrical output caused by the above phenomena, the authors extended the above parallel glove conductance-capacitance model (Figure 1(a)) to a 12-loop, 22-element equivalent circuit (Figure 1(c)). The construction of this equivalent circuit was based on the following assumptions:

- (1) The frequency dependency of the glove G and C can be represented in terms of impedance layers within a glove membrane with different parallel conductances and capacitances. These layers may be formed by membrane hydration that increase the membrane conductivity and permittivity of a latex or nitrile glove membrane.
- (2) The nonlinear relationships of the G and C with glove interfacial area, including the G maximum mentioned above, can be accounted for by a solution layer adhering to the glove as the glove is being removed from the solution. This solution layer provides a conductance-capacitance connection between the solution and the part of the glove removed from the solution.

The analysis has concentrated on the frequency dependency of glove membrane impedance, and the nonlinear relationship of glove impedance to membrane interface variation. Each impedance measurement in the experiment was conducted in a period of 276-435 seconds, and the factor of membrane hydration in the analysis was treated as a constant at the end of measurement rather than as a time variable. Although this treatment would cause slight deviation of the modeling from the real data, the complexity of the model would be greatly reduced. The variation of membrane thickness during glove movement was not considered in the analysis. The analysis did not consider the details of interfacial processes involved in the transfer of charge in an impedance analysis, that is, impedance spectroscopy. Electrokinetic potentials generated by the motion of the glove membrane in an ionic solution during the measurement was considered not significant. The impedance measurement of protective gloves was conducted under two conditions: (a) when the outer membrane of a glove was originally dry and gradually immersed in a conductive solution, and (b) when the outer membrane of a glove was originally wet, and raised and lowered in a conductive solution.

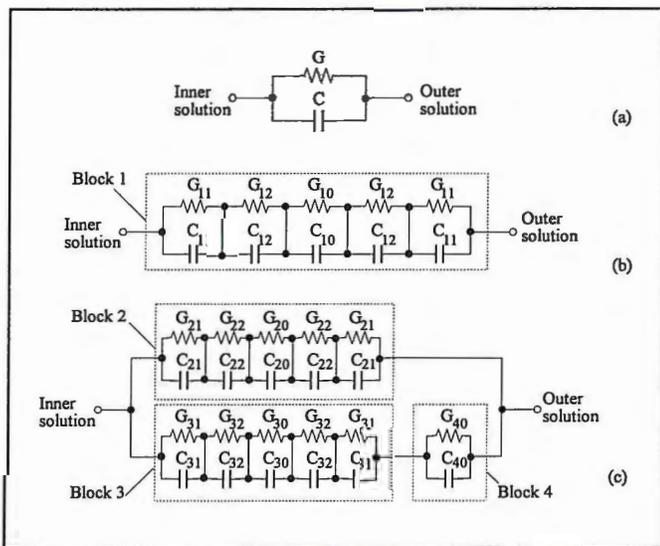


Figure 1
 (a) The total effective parallel conductance G and total effective parallel capacitance C of a glove in a conductive solution. (b) The equivalent circuit of a glove membrane with multiple-impedance layers formed by membrane hydration. (c) The equivalent circuit in dry and wet conditions.

THEORY AND MODELING

Overview of On-site Electrical Protective Glove Testing System

An on-site electrical protective glove testing system is composed of the hand of a glove wearer, the body or the body fluids of a patient, and a glove that isolates the wearer's hand from the patient's body or body fluids. One electrode is attached to the wearer's wrist and another to the patient's body, and their leads are connected to a glove tester that monitors glove integrity. This glove testing system can be simulated by an experimental glove testing system. In the simulated system, an inner conductive solution within a glove simulates the hand of a glove wearer in ideal contact with the glove; and an outer conductive solution simulates the body or the body fluids of a patient. Both aqueous solutions are composed of 0.9% NaCl to simulate the conductivity of the human hand, body and the body fluids. A glove membrane isolates the inner solution from the outer solution. Two platinum electrodes are immersed in each of the solutions, with their leads connected to a glove tester.

This solution-membrane-solution sandwich can be electrically simulated as a membrane conductance G_m in parallel with a membrane capacitance C_m (Beard, 1993). G_m , the membrane conductance, is directly proportional to the membrane interfacial area S_m , which is the area of the part of the membrane immersed in the outer solution. G_m is also inversely proportional to the membrane thickness d_m . G_m can be expressed according to:

$$G_m = \sigma_m \frac{S_m}{d_m} \quad (1)$$

where σ_m is the conductivity of the material of glove membrane (Kraus, 1984). C_m , the membrane capacitance, is also directly proportional to the membrane interfacial area S_m , and inversely proportional to the membrane thickness d_m . C_m can be expressed according to:

$$C_m = \epsilon_o \epsilon_m \frac{S_m}{d_m}, \quad (2)$$

where ϵ_o and ϵ_m are the permittivity of vacuum ($\epsilon_o = 8.85 \times 10^{-12}$ farad/m) and the relative permittivity of the membrane material, respectively (Kraus, 1984). Thus, the membrane conductance and capacitance are expected to be directly proportional to the membrane surface area, S_m .

At the moment a protective latex or nitrile glove is immersed in a conductive solution, the hydration process begins (Stampfer, 1994). The conductive solution gradually diffuses in the latex or nitrile membrane. The conductivity of the membrane gradually increases from the conductivity of natural rubber (10^{-13} - 10^{-15} siemens/m; siemens is the reciprocal of resistance, ohm) or nitrile rubber (10^{-8} siemens/m) toward the conductivity of

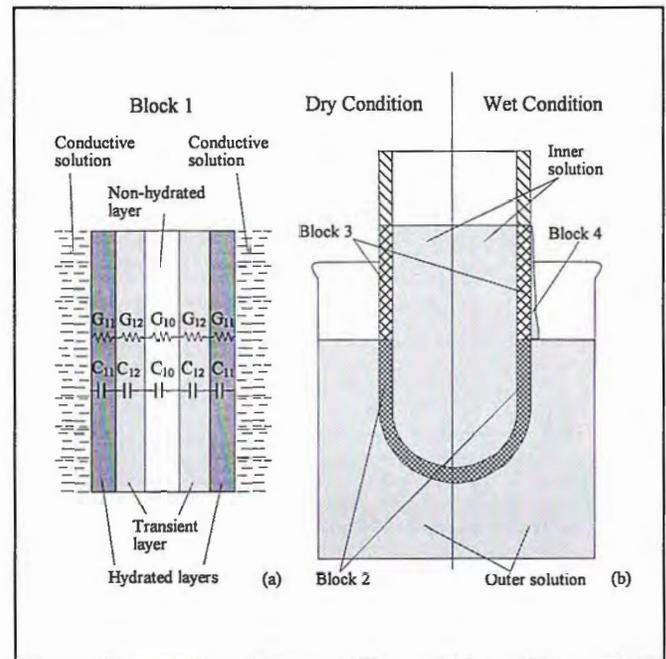


Figure 2

(a) The multiple-impedance layer formed by glove membrane hydration; G_{11} , G_{12} , and G_{10} : conductances of hydrated, transient, and non-hydrated layers, respectively; C_{11} , C_{12} , and C_{10} : capacitances of hydrated, transient, and non-hydrated layers, respectively. (b) A glove finger immersed in a conductive outer solution in both dry condition (left part) and wet condition (right part).

a conductive solution (human blood: 7×10^{-1} siemens/m). The permittivity of the membrane gradually increases from the permittivity of natural rubber (2.3-3.0) or nitrile rubber (13.0) toward the permittivity of a conductive solution (distilled water: 81) (Harper, 1975; Kraus, 1984). Since the hydration of a glove membrane gradually proceeds from the membrane-solution interface to the inside of the membrane, multiple-impedance layers with different membrane conductivity and permittivity are formed during the hydration process, as shown in Figure 2(a). The membrane layers close to the interface have higher conductivity and permittivity (G_{11} and C_{11}), and the layers inside the membrane have lower conductivity and permittivity (G_{10} and C_{10}). Based on the above assumption, an electrical model of a latex or nitrile glove membrane with hydration process was developed, which is shown in Figure 1 (b). Block 1 represents a latex or nitrile glove immersed in a conductive solution. Similar to Figure 2 (a), G_{10} and C_{10} of the equivalent circuit represent the parallel conductance and capacitance, respectively, of the inside layer of a glove membrane without hydration; the G_{11} and C_{11} represent the parallel conductance and capacitance of the outside hydrated layers; and G_{12} and C_{12} represent the parallel conductance and capacitance of the transient layers between the hydrated and nonhydrated layers. The conductivity and permittivity are lowest in the middle layer, and become higher toward the interfaces. The conductance-capacitance values of these layers depend on the parameters of the indi-

vidual layers, σ_m , ϵ_m , d_m and S_m . Block 1 of the circuit represents the total effective parallel G and C of a glove membrane.

As a glove in conductive solution is in motion, two conditions should be considered: the outer glove membrane above the outer solution is in dry condition, or is in wet condition.

Dry Condition Movement

A glove with its outer membrane above the outer solution in a dry condition can be illustrated in the left part (dry condition) of Figure 2(b). The lower part of the glove membrane (Block 2) is sandwiched by inner and outer solutions. The higher part of the membrane (Block 3) is only in contact with the inner solution. The equivalent circuit is shown in Figure 1(c). The elements G_{20} , G_{21} , G_{22} , C_{20} , C_{21} and C_{22} , which represent Block 2, and G_{30} , G_{31} , G_{32} , C_{30} , C_{31} and C_{32} , which represent Block 3, have their corresponding elements G_{10} , G_{11} , G_{12} , C_{10} , C_{11} and C_{12} , in Block 1, representing a whole glove membrane completely immersed in the solution, respectively. Since the outer membrane of Block 3 is in contact only with the air, the conductance and capacitance between it and the outer solution are very small and can be ignored. The G_{30} and C_{30} which represent the conductance and capacitance between the outer membrane of Block 3 and the outer solution, respectively, are considered to be open circuited. Only Block 2 is connected in the equivalent circuit. As a glove is immersed in the outer solution, the interfacial area S_m increases. The values of the conductive and capacitive elements of Block 2 increase from their minimum value to approach the values of their corresponding elements in Block 1, which represents a completely immersed glove. The process is reversed as a glove is lifted out of the solution.

Wet Condition Movement

In practice, the outer membrane above the outer solution is always wet when a latex or nitrile glove is frequently immersed in and lifted out of the solution. A solution layer that adheres to the outer membrane surface as the glove is being lifted from the solution is shown as Block 4 in the right part (wet condition) of Figure 2(b). By assumption, this solution layer provides a conductance-capacitance connection between the outer solution and the part of the glove above the outer solution, shown as G_{40} and C_{40} in Figure 1(c). The G_{40} and C_{40} connect the elements of Block 3 with the outer solution. As the glove moves in the outer solution, the interfacial areas of Blocks 2 and 3 vary. The values of the elements of Blocks 2 and 3 are proportional to their interfacial areas. The sum of the interfacial area of Blocks 2 and 3 is equal to the interfacial area of Block 1, where Block 1 represents the impedance of a glove completely immersed in the outer solution. Because both Blocks 2 and 3 are approximately equally hydrated in the wet condition, the elements in Blocks 1, 2 and 3 have the following relationships:

$$\begin{aligned} G_{20} + G_{30} &\approx G_{10}, \\ G_{21} + G_{31} &\approx G_{11}, \\ G_{22} + G_{32} &\approx G_{12}, \\ C_{20} + C_{30} &\approx C_{10}, \\ C_{21} + C_{31} &\approx C_{11}, \\ C_{22} + C_{32} &\approx C_{12}. \end{aligned} \quad (3)$$

As a glove is descending in the solution, the conductance G_{20} is increasing and the conductance G_{30} decreasing, and vice versa. At any moment their sum is approximately equal to the conductance G_{10} , which is the conductance of the unhydrated layer when the glove is fully immersed in the solution. The remaining five sets of the circuit elements in Equation 3 follow the same kind of the relationships.

METHODS

Two experiments were conducted to examine the developed equivalent circuit, one in the dry condition and another in the wet condition. The experiment in the dry condition was to separate the first phenomenon from the second. The experiment compared the measured total effective G and C of a protective glove in a conductive solution with the computed total effective G and C based on the equivalent circuit in the dry condition shown in Figure 1(c). This experiment examined the assumption of the hydration-caused frequency dependency of the total effective G and C in any glove position in the outer solution. It measured the total effective G and C of a protective glove finger at different frequencies while the glove finger was in motion. Only the middle fingers of protective gloves were measured in the experiment, in order to have a simple geometric shape of a glove to simplify the computer simulation. If a whole glove were used in the experiment, its complex geometry would contribute to more complicated modeling, but would show the same properties as a glove finger. In order to insure the assumption of the dry condition, a glove finger was moved in one direction downward, for gradual immersion in a conductive solution during the measurement. The experiment in the wet condition was to duplicate the phenomenon of the nonlinear relationships of the total effective G and C to the interface variation, in order to examine the assumption that the adhering solution layer was the cause of the nonlinear relationships. This experiment measured the total effective G and C of a glove finger while the outer surface of a glove finger is wet and in motion.

The experimental setup is shown in Figure 3. A glove middle finger, which was filled with 0.9% NaCl inner solution to the level of 55 mm from the finger tip, was suspended from a PVC ring. The ring was hung up by a string linked up with a stepper motor pulley. The stepper

motor was controlled by a motor controller, which was computer programmed to control the glove finger to be immersed in or lifted out of the outer solution at a given speed. The composition of the outer aqueous solution was also 0.9% NaCl. Two platinum electrodes with the diameter of 1 mm were immersed in the inner and outer solutions. The electrodes were connected with a **Solartron SI 1260 Impedance/Gain-Phase Analyzer** for the G - C measurements. Owing to the high-input impedance of the analyzer, the electrode polarization was assumed to be negligible. The measured data were sent to a Pentium™-microprocessor-based personal computer for data processing. The measurement frequencies of the analyzer were chosen to be 100, 1k, 10k, 100k and 1M Hz. The computer-programmed stepper motor controlled a constant-speed descending/ascending motion of a glove finger, except for some acceleration and deceleration at the beginning and the end of a motion, respectively. The interfacial area variation was approximately linear because of the simple cylindrical shape of glove fingers.

The total effective G and C of a glove finger was first measured in a dry condition. During the measurement, a glove finger gradually descended in the outer solution with an average speed of 0.2 mm/second in order to follow the slow frequency sweeping process of the SI 1260 impedance analyzer. The initial position of a glove finger tip was on the surface of the solution and the end position of the descending glove finger tip was 50 mm below the surface of the solution. The total effective G and C were measured in different descending positions, while the measuring frequency of the analyzer recycled the sequence of 100, 1k, 10k, 100k and 1M Hz. The dry

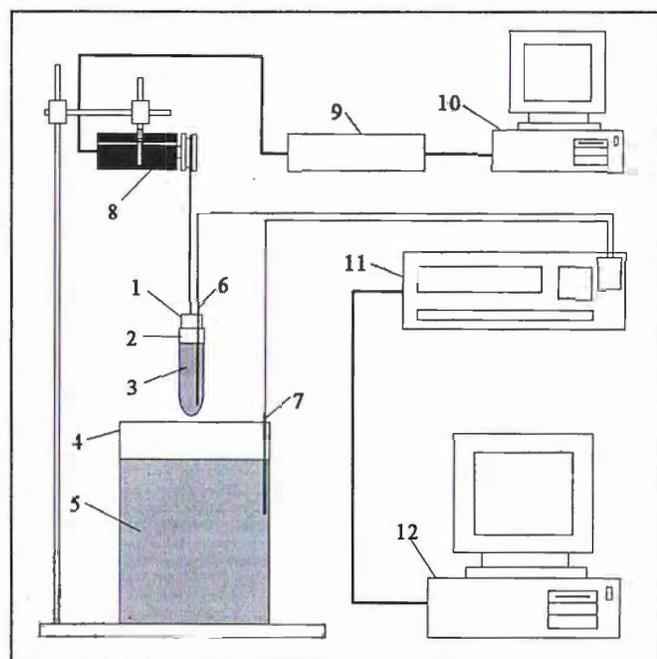


Figure 3
Experimental setup. 1 PVC ring; 2 glove finger; 3 inner solution; 4 beaker; 5 outer solution; 6 inner electrode; 7 outer electrode; 8 stepper motor; 9 stepper motor controller; 10 motor controller computer; 11 SI 1260 impedance analyzer; and 12 data acquisition computer.

condition measurement stopped as the glove finger tip descended to the end position.

In wet condition measurements, a glove finger was first immersed to the starting position where its tip was 50 mm in the solution, in order to ensure the wet membrane surface. The total effective G and C were measured while the glove finger ascended till its tip was out of the solution, and then descended back to the starting position. The measurement was repeated at four other frequencies. This one-frequency-per-motion-cycle mode increased the finger movement speed to 2.3 mm/second. The relatively faster finger movement speed prevented the wet outer surface above the solution from drying.

The total effective G and C computations in dry and wet condition were based on the equivalent circuits in Figure 1(c). In the computation for the dry condition, Blocks 3 and 4 were not connected to the outer solution. The conductance and capacitance elements of Block 2 linearly increased from nearly 0% to nearly 100% of the values of their corresponding elements in Block 1. The computation thus simulated the increase of the membrane conductance and capacitance with the increase of the membrane interfacial area with a descending glove finger. The linear relationships of the membrane conductance G_m or membrane capacitance C_m to the membrane interfacial area are expressed in Equations 1 and 2.

For the computation of the G and C in the wet condition, the conductance and capacitance elements in Block 2 linearly decreased from nearly 100% of the values of their corresponding elements in Block 1 to nearly 0%, then increased back to nearly 100%. This simulated the decrease and then the increase of the conductance and capacitance of a glove membrane, with a glove finger ascending out of, and then descending into, a conductive solution. In the meantime, the conductance and capacitance elements of Block 3 linearly increased and then decreased according to the relationships of the elements of Block 2 to block 3 described by Equation 3. Therefore, the computation simulated the conductance and capacitance of the part of a glove membrane above the outer solution as a glove is in an ascending then descending motion. The G_{40} and C_{40} of Block 4 linearly decreased from nearly 100% of their original values to nearly 0% (except C_{40} , which decreased to 50% of its value because of the stray capacitance remaining as the glove finger was out of the solution) and then increased back to nearly 100%. This simulated the conductance and capacitance of the conductive-solution layer adhering to the part of a glove membrane above a conductive solution as a glove finger is in an ascending then descending motion.

RESULTS & DISCUSSION

The total effective G and C of 15 nitrile and latex protective gloves were measured in both dry and wet conditions at five frequencies 100, 1k, 10k, 100k and 1M Hz, which are shown in Figures 4 and 5. The gloves consisted of five low-membrane-hydration-rate nitrile

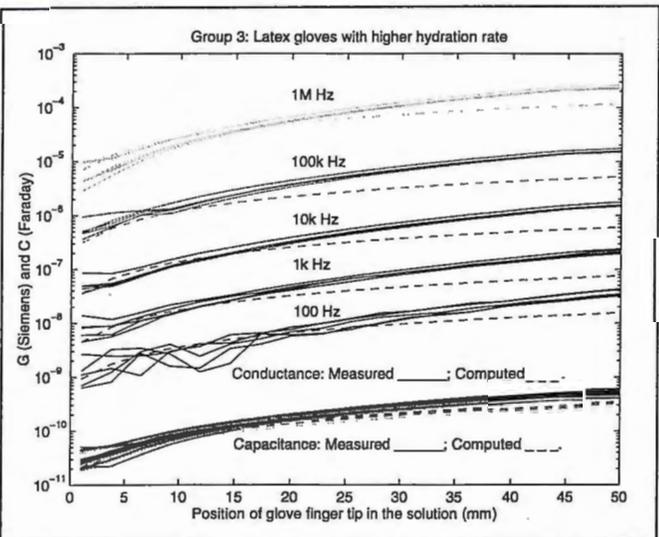
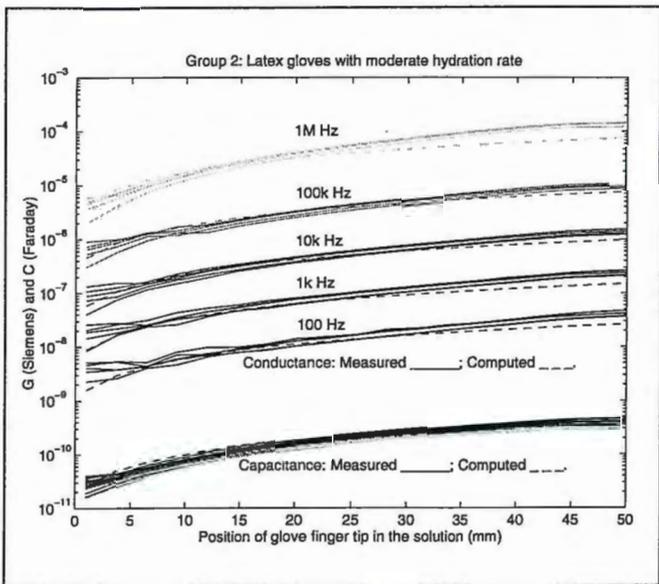
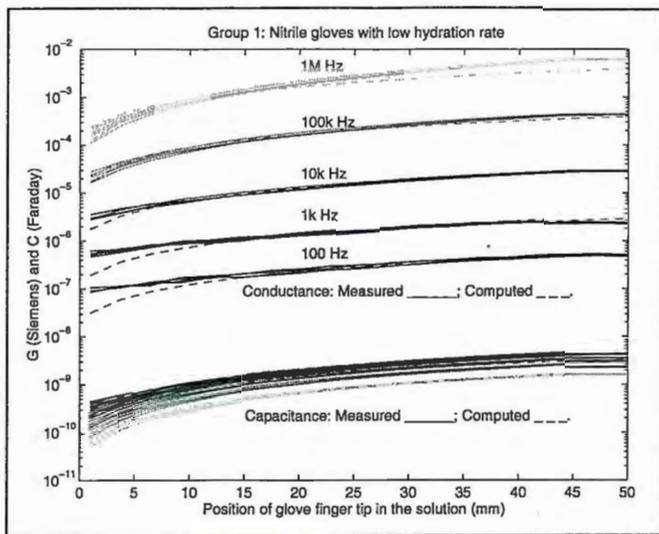


Figure 4
The measured total effective G and C of 15 glove fingers in the dry condition, and the computed total effective G and C . (a) Group 1: five low-hydration-rate glove fingers; (b) Group 2: five moderate-hydration-rate glove fingers; and (c) Group 3: five high-hydration-rate glove fingers.

medical examination gloves with lower membrane impedance, five moderate-hydration-rate latex medical surgical gloves with higher membrane impedance, and five higher-hydration-rate latex medical examination gloves with higher membrane impedance. Each type of gloves was from the same lot. The measured total effective G and C were compared with the total effective G and C computed from the equivalent circuits in the dry and wet conditions in Figure 1(c), respectively.

Dry Condition

Groups 1, 2 and 3 in Figure 4(a), (b) and (c) show the measured and the computed total effective G and C of five low-hydration-rate nitrile glove fingers, five moderate-hydration-rate latex glove fingers, and five higher-hydration-rate latex glove fingers during membrane interface variation in the dry condition, respectively. The total effective G and C of the glove fingers were measured by an SI 1260 impedance analyzer in 18 different positions as the glove finger tip descended from the outer solution surface to 50 mm below the surface. Measurements were taken at five frequencies in each position. The measured total effective G and C demonstrate that as the frequency increases at any fixed glove position, the G increases but the C decreases, and vice versa. The rate change of the total effective G and C of all three types of glove fingers with the frequency variation are similar despite the large impedance difference between the nitrile and latex gloves. At any frequency, the measured total effective G and C increased with an increase in the membrane interfacial area.

The computed total effective G and C curves in the dry condition, which were based on the equivalent circuit in Figure 1 (c), are also shown in Groups 1, 2 and 3 in Figure 4. The values of the elements of Blocks 1 were selected to simulate the characteristics of three types of gloves in the dry condition. Their values are listed in Table 1. A **MATLAB** (numeric and graphic computation software) program in the dry condition was developed to compute the total effective G and C of three different types of glove fingers in 18 different positions and at five different source frequencies. For low-hydration-rate nitrile gloves (see Group 1 in Fig. 4), the computed total effective G and C matched the measured G and C . This match proved the assumption that the frequency dependency is caused by the multiple-impedance layers formed by the membrane hydration. The latex gloves with moderate and high hydration rates (see Groups 2 and 3 in Figure 4, respectively) have slopes of the measured total effective G and C slightly steeper than the computed total effective G and C . The higher the hydration rate, the steeper the measured curves' slopes are relative to the computed slopes. This slope discrepancy can be attributed to the increasing of glove membrane hydration during the measurements. The computer modeling only simulated a fixed moment of a glove membrane hydration process. Thus this model could not follow the process of membrane hydration.

Wet Condition

Groups 1, 2 and 3 in Figure 5(a), (b) and (c) show the measured and computed total effective G and C of the five low-hydration-rate nitrile glove fingers, five moderate-hydration-rate latex glove fingers and five higher-hydration-rate latex glove fingers in a wet condition, respectively. Each of the glove fingers repeated the ascending-then-descending motion cycle at each of the five frequencies as described above. At lower frequencies, the effect of C_{40} on Block 4 is negligible; the admittance of Block 4 is predominated by the adhering layer conductance G_{40} . Because G_{40} is much larger than total effective admittance of a glove (especially for latex gloves), the total effective admittance of a glove is approximately equal to the sum of the admittance of the glove membrane in the solution (Block 2) and that above the solution (Block 3). The calculations of the admittances of Blocks 2 and 3, based on the relationships defined by equation 3, show that the sum admittance of Blocks 2 and 3 approaches the total effective admittance of a glove at any glove position in the solution. The changes of the total effective G and C versus the glove movement thus were barely noticeable at lower frequencies, especially for latex gloves. The membrane capacitances C_{10} , C_{11} and C_{12} are larger than the adhering layer capacitance C_{40} . As the measuring frequency increases, the total effective admittance of a glove becomes comparable with or even larger than the adhering layer admittance. The simple relationship of the total effective admittance with the glove movement becomes nonlinear.

In the starting position where a glove finger tip was 50 mm below the solution surface, the frequency dependency of the total effective G and C was observed to be the same as in the dry condition. As the glove finger ascended from the starting position, a maximum in total

effective G was observed at certain frequencies. As a glove finger ascended from the solution, the interfacial area decreased, resulting in an increasing total effective G until reaching its maximum, and then decreased. This maximum occurred at around 1 kHz for nitrile gloves and at around 100 kHz for latex gloves. The magnitudes of the G maxima for latex gloves is about two times higher than the initial G magnitude when a glove finger was completely immersed in the solution. For unknown reason, these G maxima for the nitrile gloves were not

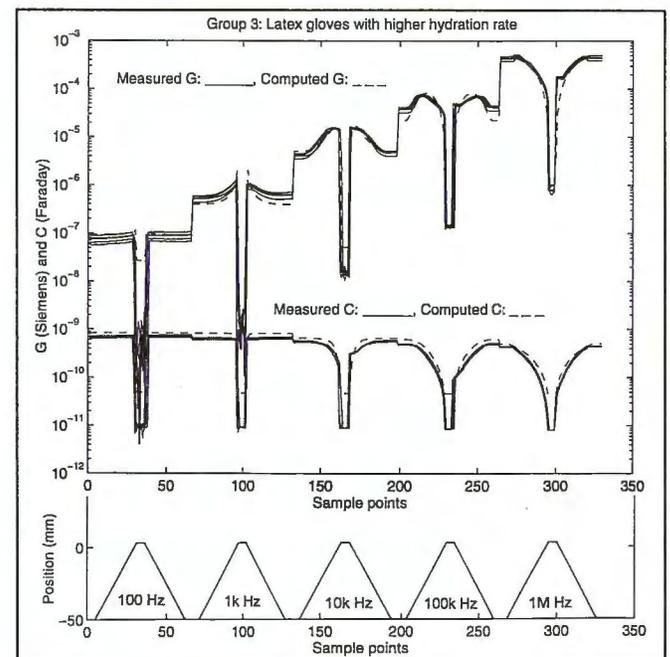
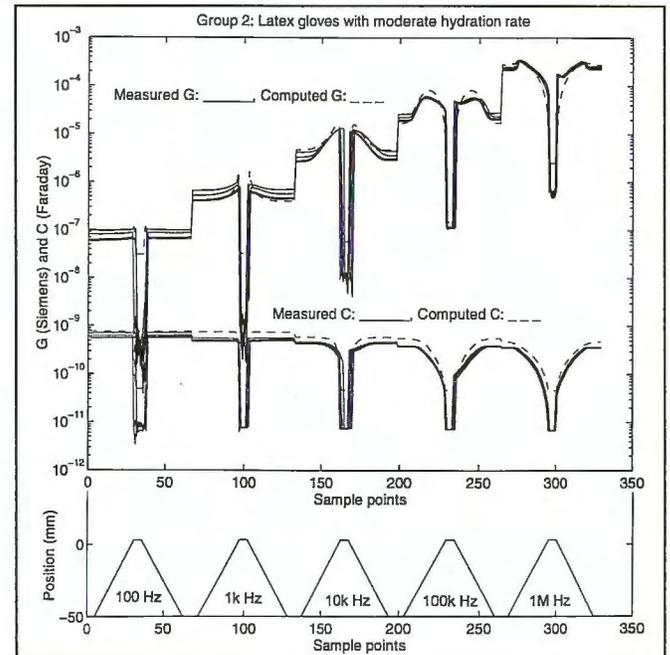
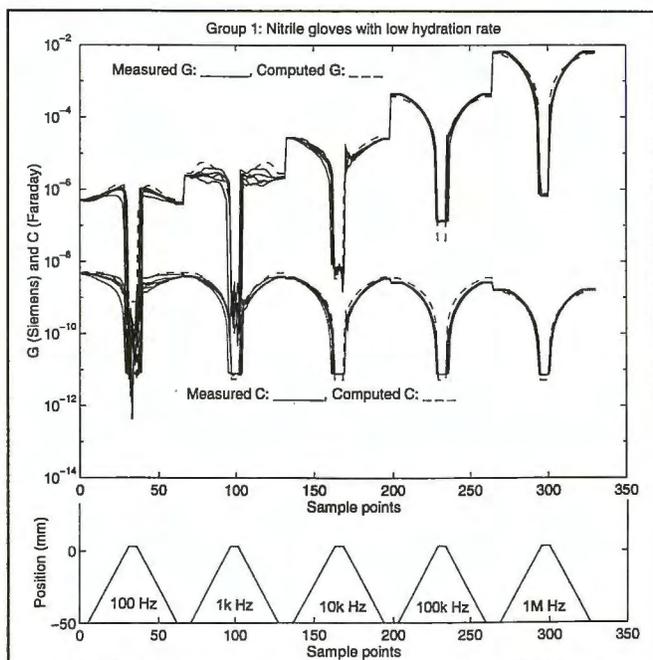


Figure 5
The measured total effective G and C of 15 glove fingers in the wet condition, and the computed total effective G and C . (a) Group 1: five low-hydration-rate glove fingers; (b) Group 2: five moderate-hydration-rate glove fingers; and (c) Group 3: five high-hydration-rate glove fingers.

as stable as those for the latex gloves. Before reaching the total effective G maximum, the magnitude of G is inversely related to the glove interfacial area; and after the G maximum, it is directly related to the interfacial area. This relationship was symmetrical when the glove finger descended from its highest position (3 mm above the solution surface). The glove position of the total effective G maximum is frequency dependent. At lower measurement frequencies, a total effective G maximum began to appear at a higher position of a glove finger. As the frequency increased, the total effective G maximum shifted toward the lower glove position, and then disappeared. The changing of the total effective C is consistently and directly related to the glove interfacial area. The smaller the interface, the smaller the magnitude of C , and vice versa. The slope of the total effective C is also source-frequency dependent.

The computed total effective G and C curves in the wet condition, which were based on the equivalent circuit in Figure 1(c), are also shown in Groups 1, 2 and 3 in Figure 5. The selected element values of Blocks 1 and 4 to match the electrical characteristics of the three types of glove fingers are listed in Table 1. A MATLAB program for the wet condition was developed to compute the total effective G and C of these three different types of glove fingers in five identical glove-motion cycles, each at one of the five frequencies mentioned above. The computed total effective G and C properly simulated the measured total effective G and C with the properties described above. This close simulation between the measured and computed total effective G and C proved the assumption that the wet surface connection is the key factor causing the above phenomenon. Shown in the equivalent circuit in Figure 1(c), the connection of Block 3-Block 4 series to the outer solution causes the appearance of the total effective G maximum as the interfacial area of a glove membrane varies. This connection also causes the position of the total effective G

maximum to be frequency dependent. Comparing the values of the wet surface elements for nitrile gloves with those for latex gloves in Table 1, it can be seen that G_{40} for nitrile gloves is nearly 42 to 50 times lower than that for the latex gloves, and C_{40} for the nitrile gloves are 10 times lower than that for the latex gloves. Because the conductivity and permittivity of the solution adhering to the outer membrane surface of both the nitrile and the latex gloves are the same, this conductance and capacitance discrepancy can be attributed to the differences in adhesion of the aqueous solution to the glove membranes. This factor affects the thickness of the solution layer clinging to the membranes. The adhesion of a glove membrane certainly affects the frequency and the glove position, where the total effective G maximum appears.

Considerations for Glove Tester Design

To determine the penetration threshold of a glove tester using the total effective G as the penetration indicator, a designer has to consider the effect of frequency dependency of intact total effective G and C of the protective gloves on penetration detection accuracy. The intact total effective G of gloves increases with the increase in the testing frequency. The penetration threshold should be adjusted according to this total effective G variation to avoid false penetration alarms or false positives. The total effective G maximums and the inverse relationship between the G and the interfacial area affect the penetration-detection accuracy and sensitivity of a glove tester. To determine the threshold of a glove tester, the highest intact glove conductance during testing should be determined. A designer cannot simply assume the total effective G of the deepest glove position as the highest intact glove conductance. The G maximum occurred during the glove movement may exceed the G in deepest position.

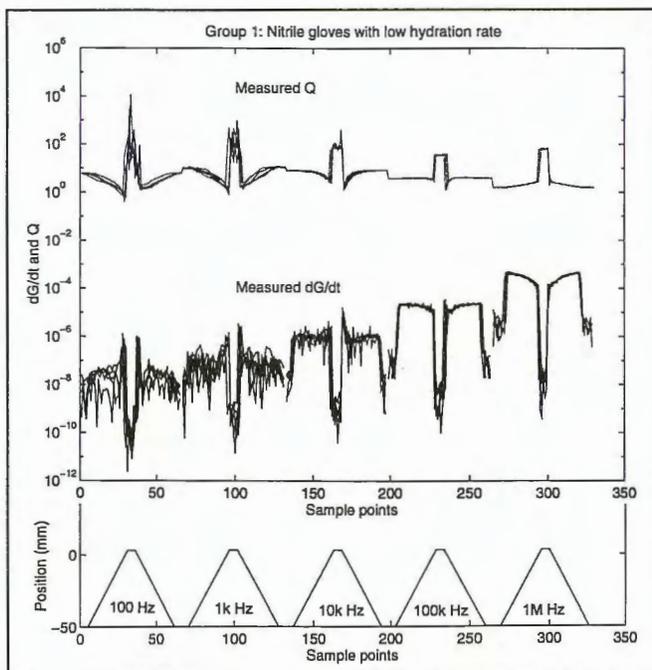
Designers of glove testers whose penetration indica-

Table 1
Values of the equivalent circuit elements of Block 1

Glove conditions				Values of the equivalent circuit elements of Block 1							
Type	Impedance	Hydration rate	Outer surface	G_{10} (S)	C_{10} (F)	G_{11} (S)	C_{11} (F)	G_{12} (S)	C_{12} (F)	G_{40} (S)	C_{40} (F)
Nitrile	Low	Low	Dry	5.0e-07	5.0e-09	2.5e-02	5.0e-09	6.7e-04	2.5e-08	0.0e+00	0.0e+00
			Wet	5.0e-07	5.0e-09	3.0e-02	3.5e-09	8.0e-04	3.0e-08	7.0e-06	1.0e-11
Latex	High	Moderate	Dry	2.5e-08	4.5e-10	1.7e-02	7.0e-09	1.1e-04	6.0e-09	0.0e+00	0.0e+00
			Wet	9.5e-08	7.7e-10	2.0e-02	4.9e-09	1.4e-04	4.2e-09	3.5e-04	1.0e-10
Latex	High	High	Dry	1.5e-08	3.5e-10	1.7e-02	4.0e-09	1.4e-04	7.0e-09	0.0e+00	0.0e+00
			Wet	9.0e-08	8.4e-10	1.8e-02	3.6e-09	1.7e-04	4.9e-09	3.0e-04	1.0e-10

Table 1 Values of the equivalent circuit elements of Block 1.

tor is the change rate of the total effective glove conductance dG/dt should consider the effect of the total effective G maximum during a glove movement on the fluctuation of the conductance derivative dG/dt . The dG/dt changes its sign around the total effective G maximum. This dG/dt fluctuation seriously affects the penetration-detection accuracy. The dG/dt also fluctuates at the moment a tested glove leaves or re-enters the conductive solution. If no total effective G maximum appears before the glove is out of the solution when the glove is ascending from a conductive solution, the flat or the rising total effective G with an ascending glove causes a strong dG/dt fluctuation at the moment the glove leaves the solution. If a total effective G maximum appears before the glove is out of the solution, the direct G -interface relationship would cause a smaller dG/dt fluctuation at the same time. The earlier the total effective G maximum appears as the glove ascends, the smaller the dG/dt fluctuation occurs at the moment the glove leaves the solution. The fluctuation of dG/dt as a glove re-enter the solution has a symmetrical effect. Groups 1, 2 and 3 in Figure 6(a), (b) and (c) show the $|dG/dt|$ of the same sets of the glove fingers in wet condition in the same measurements in Figure 5. The absolute values of the dG/dt were selected so that the data could be shown in logarithmic scale. The influence of the total effective G maximum on the dG/dt at the moments the gloves leave and re-enter the solution can be clearly observed. For example, at 10 kHz, the relationship of the total effective G with the interfacial area is direct for Group 1 gloves, but inverse for Group 2 gloves; thus, the leaving/re-entering dG/dt fluctuation of Group 1 gloves is smaller than that of Group 2 gloves. Because the appearance of the total effective G maximum is frequency dependent, the dG/dt fluctuations are also frequency dependent.



For the design of a glove tester using a Q factor as the penetration indicator, a designer should consider the effect of frequency dependency of the total effective G and C , and the effect of inverse G -interface relationship on Q variation. The frequency dependency of the G and C causes the variation of the Q at different frequencies. The inverse G -interface relationship causes the decrement of the Q value as a glove ascends in the conductive solution, which may cause false penetration alarms. Groups 1, 2 and 3 in Figure 6 (a), (b) and (c) show the Q factors of the same sets of the gloves in wet condition in

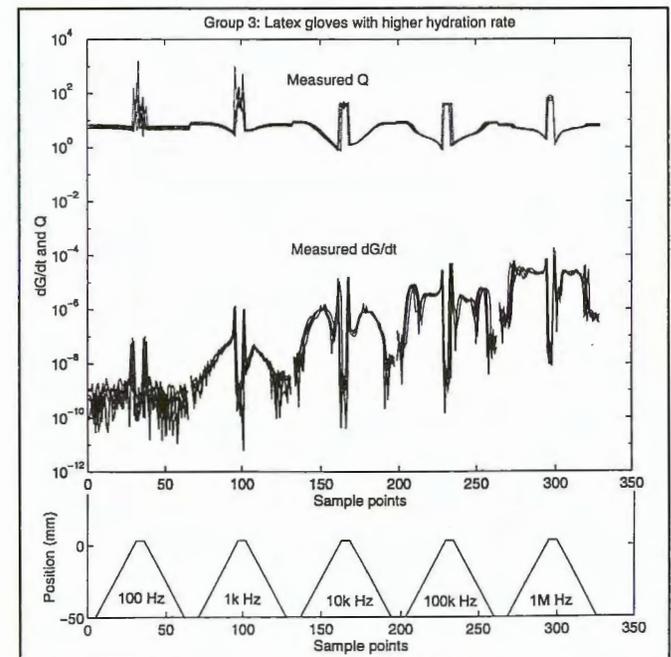
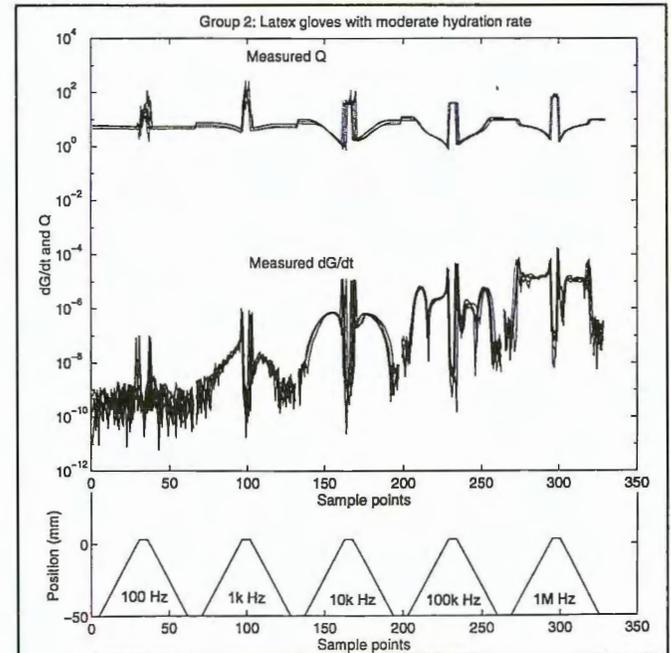


Figure 6
The $|dG/dt|$ and $Q (\omega C/G)$ of the 15 glove fingers in the wet condition, in the same measurements in Figure 5. (a) Group 1: five low-hydration-rate glove fingers; (b) Group 2: five moderate-hydration-rate glove fingers; and (c) Group 3: five high-hydration-rate glove fingers.

the same measurements as in Figure 5. The frequency dependency of the Q factor and the G factor decrease caused by G -maximum are noticeable.

CONCLUSIONS

The equivalent circuits in Figure 1(b) and (c) properly simulate the total effective G and C of protective gloves in dry and wet conditions. The frequency dependency of the total effective G and C is caused by the multiple-impedance layers formed by glove membrane hydration. The nonlinear relationships of the total effective G and C with the glove interfacial area is caused by the conductive solution layer adhering to the outer glove membranes. The total effective G maximum is dependent of measurement frequency, glove membrane impedance and solution adhesiveness of the membrane. The frequency dependency of total effective G , the G maximum and the inverse relationship of total effective G to interface may seriously affect the accuracy and the sensitivity of the electrical glove testers using G , dG/dt or Q as the penetration indicator. The tester using Q as the penetration indicator is also affected by the frequency dependency of the total effective C .

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BIOGRAPHIES

SHENGKE ZENG

Shengke Zeng received his Ph.D. degree in biomedical engineering from Drexel University, Pennsylvania. He is currently a visiting associate at the National Institute for Occupational Safety and Health, Division of Safety Research, Morgantown, West Virginia. His research interests include biomedical engineering application to occupational safety and health problems.

RICHARD B. BEARD

Richard B. Beard received the B.S. degree in chemical engineering from Northeastern University, the S.M. degree in electrical engineering from Harvard University and the Ph.D. degree from the University of Pennsylvania. He is presently the Lester Kraus emeritus professor of electrical and computer engineering and a professor of the Biomedical Engineering and Science Institute of Drexel University. His research interests include the development of techniques and instrumentation for improving and monitoring the integrity of protective barriers.

STEPHEN P. BERADINELLI

Stephen P. Berardinelli, Sr., received his Ph.D. From the University of Rhode Island in Chemistry. He holds the rank of Captain in the U.S. Public Health Service Commissioned Officer Corps and is currently stationed in Morgantown, WV with the National Institute for Occupational Safety and Health, Division of Safety Research. His research has focused on the performance of personal protective equipment used in the workplace.

Address all correspondence and reprint requests to Shengke Zeng, NIOSH/DSR, 1095 Willowdale Road, Morgantown, WV 26505; Telephone: (304)285-5971; FAX: (304)285-6047.