New Method of On-Site Detection of Non-conductive and Conductive Penetrations of Protective Gloves

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A new method to detect protective glove penetration in conductive solution was developed to increase penetration detection sensitivity and accuracy. Penetration by non-conductive materials was detected by a penetration indicator, which is the ratio of the glove-conductance time derivatives to the glove-capacitance time derivatives. Penetration by conductive materials was detected by a penetration indicator, which is the product of glove conductance time derivative and the glove capacitance time derivative. The comparison tests showed that under the test conditions the signal-to-noise ratio (signal is referred to the maximum magnitude of a penetration indicator during penetration, and the noise is referred to that during membrane hydration and glove movement) of this method is higher than other existing methods in both non-conductive and conductive penetration detections.

Index under: *Gloves; Latex Gloves; Nitrile Gloves; Glove tester; Electrical conductance; Electrical capacitance; Differentiation.*

INTRODUCTION

The penetration indicator of an on-site electrical glove tester continuously measures the impedance variation of a protective glove in conductive solution, such as human body fluids, in order to detect any penetration of the glove membrane. When a protective glove is penetrated during use, the magnitude of the penetration indicator should exceed a predetermined threshold, and the glove tester should detect this variation and activate a tester alarm. The known and published glove tester methods employ one of the following three types of impedance parameters as their glove penetration indicator: glove conductance (conductance indicator) (Albin, 1990, 1992; Beck, 1961; Leach, 1993; Langdon, 1990); the time derivative of glove conductance (derivative indicator) (Williams, 1992; Cox, 1994; Stampfer, 1996); or the glove quality factor Q (Q indicator) (Beard, 1993). The testers using these penetration indicators have sensitivity and accuracy limitations in on-site penetration detection. During on-site glove testing, when a glove is penetrated by non-conductive materials, such as a piece of glass or a bone fracture, the individual variations of glove conductance, glove quality factor Q, or glove-conductance time derivative are all small. These small indicator variations limit the penetration-detection sensitivity of all three tester types mentioned above. The accuracy limitation of these glove testers is mainly caused by glove membrane hydration and glove movement in conductive solution. Glove membrane hydration during on-site glove testing causes continuous up-shifting of the glove conductance (Stampfer, 1994). The up-shifted glove conductance may exceed the threshold of the testers using glove conductance and may cause false alarms, thereby reducing the penetration detection accuracy. In on-site glove testing, a glove is always being moved in a conductive solution, or even pulled out of and re-immersed in the

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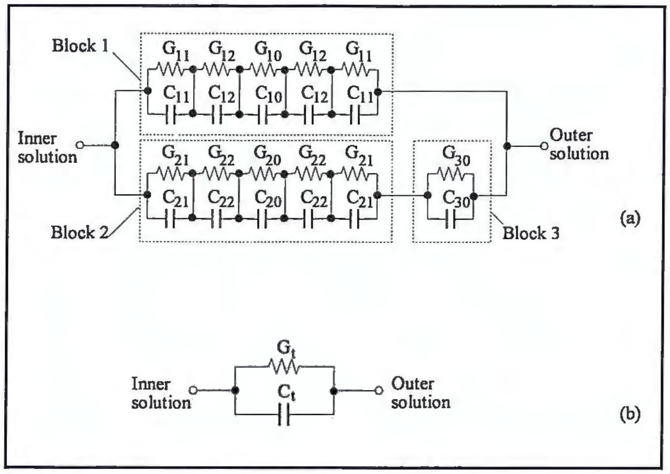

FIGURE 1

Equivalent circuits of a protective glove in conductive solution.

solution. This glove movement causes membrane impedance fluctuation, especially the fluctuation of a glove-conductance time derivative, and may also falsely activate a tester alarm.

This paper establishes a new penetration-detection method to boost penetration-detection sensitivity, and to reduce the effects of glove membrane hydration and glove movement on penetration-detection accuracy. This method separates non-conductive glove penetrations (glove penetrated by non-conductive material) from conductive glove penetrations (glove penetrated by conductive material), and chooses different penetration indicators to detect these two types of penetrations. This method first differentiates the glove conductance and capacitance, and then

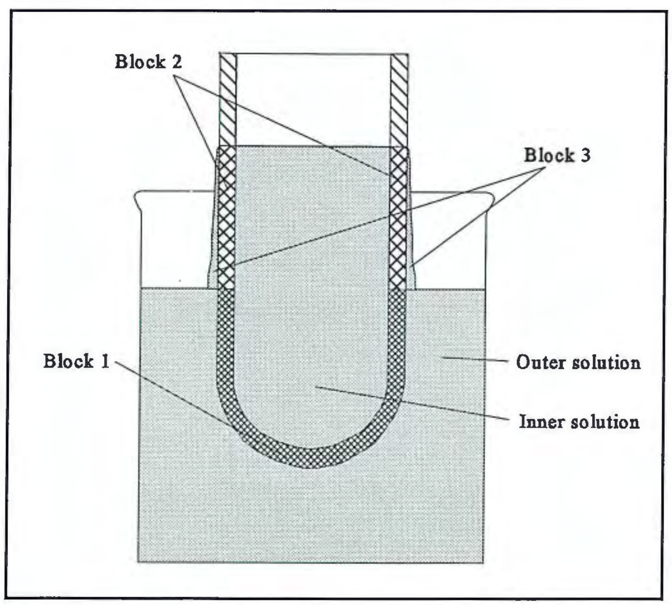

FIGURE 2

A protective glove finger with inner and outer solution and adhering solution layer.

chooses their ratios and product to detect non-conductive and conductive penetrations, respectively. Theoretical analysis and penetration experiments were conducted to confirm the increased sensitivity and accuracy of glove penetration detection.

THEORY

Protective Glove Model

An on-site electrical protective glove testing system can be thought of as a "wearer's-hand / glove-membrane / patient's-body-fluid" sandwich. Two electrodes from an electrical glove tester are attached to the wearer's hand and the patient's body to detect the electrical impedance variation of the mentioned sandwich. This glove testing system can be simulated by an experimental glove testing system composed of a "inner-solution / glove-membrane / outer-solution" sandwich. The inner and outer conductive solutions (0.9% NaCl) simulate the wearer's hand and patient's body fluid, respectively. As the conditions of membrane hydration and glove movement in conductive solution are considered, the impedance of the glove testing system can be described by an equivalent circuit shown in Fig. 1(a) (Zeng, 1996). Block 1 of the circuit (G_{10}-G_{12}, and C_{10}-C_{12}) represents the impedance of that part of the glove membrane immersed in the outer solution, and Block 2 (G_{20}-G_{22}, and C_{20}-C_{22}) the impedance of that part of the membrane above the outer solution. Block 3 (G_{30} and C_{30}) represents the impedance of the solution layer adhering to the part of the outer membrane above the outer solution. Blocks 1 and 2 of a glove finger with inner and outer solutions and an adhering solution layer are shown in Fig. 2 (Zeng, 1996). The total parallel conductance G_t and capacitance C_t of the equivalent circuit are shown in Fig. 1(b). The three mentioned penetration indicators — the conductance indicator, the derivative indicator and the Q indicator — can be defined by the total parallel conductance and/or capacitance as G_t, $d/dt(G_t)$ and $\omega C_t/G_t$, respectively. As proven by Zeng et al. (1996), the total conductance G_t and capacitance C_t are source frequency dependent and the variation of G_t and C_t is non-linear to the glove position in conductive solution. Also G_t fluctuates when first immersed in conductive solution (due to electrical charging) and then gradually up-shifts (due to membrane hydration) (Stampfer, 1994).

Non-conductive Membrane Penetration

Non-conductive penetration is defined as that occurring when a barrier membrane is penetrated by a non-conductive material, such as a thorn or bone fracture, or is torn by external force. Due to the influx of the conductive solution through the hole(s) by non-conductive penetration, the penetrated total parallel glove conductance G_t' and capacitance C_t' are different from un-penetrated parallel glove conductance G_t and capacitance C_t, respectively. This influx solution forms a hole conductance G_{bnc} and a hole capacitance C_{bnc} parallel with the surrounding intact membrane conductance $G_t(S_m - S_p)$ and capacitance $C_t(S_m - S_p)$, where S_m is the area of whole membrane and S_p the penetrated membrane area. Since $S_m >> S_p$, then $G_t(S_m - S_p) \approx G_t$ and $C_t(S_m - S_p) \approx C_t$. The non-conductively penetrated total glove conductance G_t' and capacitance C_t' can be determined by Eqs. 1 and 2 (Kraus, 1984):

$$G'_t \approx G_t + G_{hnc} = G_t + \sigma_s \frac{S_p}{d_m} \quad (1)$$

and

$$C'_t \approx C_t + C_{hnc} = C_t + \in_o \in_s \frac{S_p}{d_m} \quad (2)$$

where σ_s is the conductivity of conductive solution (7×10^{-1} siemens/m for human blood), d_m, the membrane thickness (≈ 0.1 mm); $\in_o$, permittivity of vacuum (8.85×10^{-12} farad/m); and $\in_s$, the relative permittivity of the influx solution (81 for distilled water) (Harper, 1975; Kraus, 1984). The equivalent circuit of non-conductively penetrated glove impedance is shown in Fig. 3(a). The existing data (Zeng, 1996) show that the conductance and capacitance values of a typical latex surgical glove finger are 9.8×10^{-7} siemens and 3.9×10^{-10} farad, respectively, and those of a typical nitrile medical examination glove finger are 2.9×10^{-5} siemens and 3.7×10^{-9} farad (the impedances were measured as a glove finger was fully immersed in a conductive solution at the measuring frequency of 10 kHz). Considering a 10-micron-diameter hole in a glove membrane, the penetrated area S_p is 8×10^{-5} mm^2. Substituting the values of σ_s, $\in_o$, $\in_s$, S_p, and d_m into Eqs. 1 and 2, the hole conductance $G_{bnc} = 5.6 \times 10^{-7}$ siemens, and hole capacitance $C_{bnc} = 5.7 \times 10^{-16}$ farad. The ratio of glove conductance after penetration to that before penetration, G_t' / G_t, is 1.57 for a latex glove and 1.02 for a nitrile glove. These lower ratios indicate that the conductance indicator G_t has a lower penetration detection sensitivity in non-conductive penetration tests, especially for nitrile gloves. It is also seen that the ratio of glove capacitance after penetration to that before penetration, C_t' / C_t, is about 1 for both gloves. This almost unvaried glove capacitance indicates that the penetration detection sensitivity of the Q indicator $\omega C_t / G_t$ is also low in non-conductive penetration, similar to that of the conductance indicator G_t. In contrast, the derivative indicator $d/dt(G_t)$ performs better than the above two indicators in non-conductive penetration, due to its nature of differentiation. Its increment ΔG_t ($\Delta G_t = G_t' - G_t$) during penetration (5.6×10^{-7} siemens) is tremendous compared with that without penetration (≈ 0). The derivative indicator has high immunity to the membrane-hydration-caused indicator shifting, due to the fact that its differential magnitude is great for rapid changing signals (penetration) and very small for gradual changing signals (membrane hydration). The derivative indicator is less immune to the glove-movement-caused magnitude fluctuation, since its differential magnitude in sudden glove movement is also great and comparable to that in glove penetration.

In order to overcome the reduced immunity to glove movement, a new penetration indicator can be constructed as the ratio of differentiated glove conductance to capacitance, $|d/d_t(G_t) \,/\, d/d_t(C_t)|$. During the same 10-micron-diameter non-conductive penetration, the glove conductance increment $|\Delta G_t|$ is the same as the derivative indicator (5.6×10^{-7} siemens), but the capacitance increment $|\Delta C_t|$ is trivial (5.7×10^{-16} farad) for both latex and nitrile gloves. During membrane hydration, the capacitance increment $|\Delta G_t|$ is also trivial and is similar to that in non-conductive penetration. Therefore, the immunity of $|\Delta G_t / \Delta C_t|$ to membrane hydration is similar to that of the derivative indicator $d/dt(G_t)$. In the case of glove movement, it can be seen from the existing data (see C_t curves in glove movement in Zeng, 1996) that the $|\Delta C_t|$ caused by glove movement in conductive solution is much greater than that caused by non-conductive penetration (5.7×10^{-16} farad). In rapid glove movement, the increment $|\Delta Gt|$ is often comparable to that in non-conductive penetration. Because $|\Delta C_t|_{glove\ movement} >> |\Delta C_t|_{\text{non-conductive penetration}}$, the $|\Delta G_t / \Delta C_t|$ during glove movement should be much smaller than that in non-conductive penetration. This demonstrates the high immunity of the indicator $|d/dt(G_t) \,/\, d/dt(C_t)|$ to the magnitude fluctuation caused by glove movement.

The variations of higher-order time derivatives, $|d^2/dt^2(G_t) \,/\, d^2/dt^2(C_t)|$ and $|d^3/dt^3(G_t) \,/\, d^3/dt^3(C_t)|$ have the same properties as the first order derivative $|d/dt(G_t) \,/\, d/dt(C_t)|$. Furthermore, these different-order time derivatives line up at the beginning of a penetration. In practice, a more sophisticated non-conductive penetration indicator

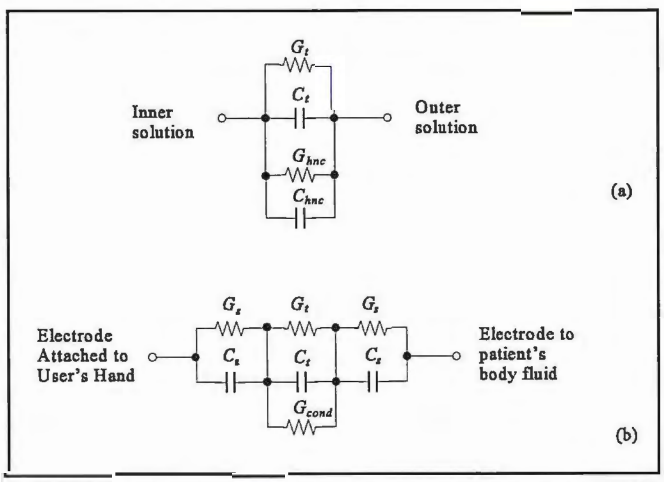

FIGURE 3

Equivalent circuits of non-conductive penetration (a) and conductive penetration (b).

was constructed as $|d/dt(G_t) \ / \ d/dt(C_t) \bullet d^2/dt^2(G_t) \ / \ d^2/dt^2(C_t) \bullet d^3/dt^3(G_t) \ / \ d^3/dt^3(C_t)|$ (will be called the Multi-Ratio indicator in the following). This non-conductive penetration indicator can further reduce the indicator fluctuations caused by membrane hydration and glove movements, since the maxima of different-order time derivatives, $|d/dt(G_t) \ / \ d/dt(C_t)|_{max}$, $|d^2/dt^2(G_t) \ / \ d^2/dt^2(C_t)|_{max}$, and $|d^3/dt^3(G_t) \ / \ d^3/dt^3(C_t)|_{max}$, are not synchronized as well during membrane hydration or during glove movement as during non-conductive penetration.

Conductive Membrane Penetration

Conductive penetration is defined as that occurring when a barrier membrane is penetrated by a conductive material, such as a metal needle, etc. During conductive penetration, the membrane conductance and capacitance are parallel to the conductance of a conductive material, G_{cond}, as shown in Fig. 3(b). Since the G_{cond} value is very large, it almost short circuits the intact glove conductance $G_t(S_m - S_p)$ ($\approx Gt$) and capacitance $C_t(S_m - S_p)$ ($\approx C_t$), and causes an instantaneous increase of the total conductively penetrated glove conductance G_t'' and capacitance C_t''. To calculate G_t'' and C_t'', the intact glove impedance ($G_t + j\omega C_t$), which is parallel to G_{cond}, can be negligible, since its magnitude is much smaller than G_{cond}. But the impedance of inner and outer solutions ($G_s + j\omega C_s$), which is in series with G_{cond}, cannot be ignored, because its magnitude is much smaller than G_{cond}. In contrast, in non-conductive penetration analysis, the ($G_s + j\omega C_s$) was negligible because its magnitude is much greater than that of the intact glove membrane impedance ($G_t + j\omega C_t$), which is in series with ($G_s + j\omega C_s$). The conductively penetrated glove impedance ($G_t'' + j\omega C_t''$) is calculated in Eq. 3:

$$G_t'' + j\omega C_t'' \approx \left[\frac{1}{G_s + j\omega C_s} + \frac{1}{G_{cond}} + \frac{1}{G_s + j\omega C_s}\right]^{-1} \approx \frac{1}{2}(G_s + j\omega C_s). \quad (3)$$

Since the total glove impedance suddenly jumps from intact glove membrane impedance ($G_t + j\omega C_t$) to approximately the conductive solution impedance $1/2(G_s + j\omega C_s)$, the increments ΔG_t and ΔC_t are enormous. The ΔG_t and ΔC_t occur instantaneously during conductive penetration, so that the variations of $d/dt(G_t)$ and $d/dt(C_t)$ are highly synchronous. The magnitudes of $d/dt(G_t)$ and $d/dt(C_t)$ are directly related to the conductivity and size of the penetrating conductive material, and size of the penetrated hole. A conductive penetration indicator can therefore be constructed as $d/dt(G_t) \bullet d/dt(C_t)$ (called the "Product indicator" in the following), in order to amplify the indicator variation during conductive penetration.

The Product indicator $d/dt(G_t) \bullet d/dt(C_t)$ also has a certain degree of immunity to glove membrane hydration and glove movement in conductive solution. The increments ΔG_t and ΔC_t caused by membrane hydration and glove movement are much less than those caused by conductive penetration. The maxima of ΔG_t and ΔC_t are less synchronized with each other in membrane hydration and glove movement than during conductive penetration. It is expected that the Product indicator would have a high magnitude ratio of conductive penetration to membrane hydration, and a high magnitude ratio of conductive penetration to glove movement. To compare these two magnitude ratios of the Product indicator with those of the derivative indicator $d/dt(G_t)$, let ΔG_p and ΔC_p be the increments of G_t and C_t during conductive penetration, and ΔG_f and ΔC_f be the fluctuations of the G_t and C_t during membrane hydration and glove movement, respectively. The ratio of penetration to fluctuation of the Product indicator can be expressed as $(\Delta G_p \bullet \Delta C_p) \ / \ (\Delta G_f \bullet \Delta C_f)$, and that of the derivative indicator as $\Delta G_p \ / \ \Delta G_f$. Since $\Delta C_p >> \Delta C_f$, then $(\Delta G_p \bullet \Delta C_p) \ / \ (\Delta G_f \bullet \Delta C_f) >> \Delta G_p \ / \ \Delta G_f$. To compare the ratio of penetration to fluctuation of the Product indicator with that of the conductance indicator G_t and the Q indicator $\omega C_t/G_t$, let this ratio of the conductance indicator, G_t, be G_t''/G_f and this ratio of the $1/Q$ indicator, $1/(\omega C_t/G_t)$, be $1 \ / \ [(\omega C_t''/G_t'') \ / \ (\omega C_f/G_f)] = (G_t'' \bullet C_f) \ / \ (C_t'' \bullet G_f)$, where G_f and C_f are the magnitudes of G_t and C_t during membrane hydration and glove movement, respectively. Since $G_t'' >> G_t$, then $\Delta G_p = G_t'' - G_t \approx G_t''$. Since $G_f > G_t$, then $\Delta G_f = G_f - G_t < G_f$. Thus, $\Delta G_p \ / \ \Delta G_f > G_t'' / \ G_f$. And since $\Delta C_p \ / \ \Delta C_f >> 1$, then $(\Delta G_p \bullet \Delta C_p) \ / \ (\Delta G_f \bullet \Delta C_f) >> G_t''/ \ G_f$. Since $C_t'' >> C_f$, then $C_f \ / \ C_t'' << 1$. Thus $G_t''/ \ G_f >> (G_t'' \bullet C_f) \ / \ (C_t'' \bullet G_f)$, and $(\Delta G_p \bullet \Delta C_p) \ / \ (\Delta G_f \bullet \Delta C_f) >> (G_t'' \bullet C_f) \ / \ (C_t'' \bullet G_f)$. Therefore, it is concluded that the ratio of conductive penetration to fluctuation (caused by both membrane hydration and glove movement) of the Product indicator is much greater than that of the conductance indicator, the derivative indicator and the Q indicator.

Higher order time derivatives are not included in the Product indicator, since the first order derivative already provides enough sensitivity and accuracy to detect even very small size conductive penetration.

GLOVE TESTER DESIGN

The block diagram of a glove tester based on the combination of the Multi-Ratio indicator and the Product indicator is shown in Fig. 4. The glove tester consists of three sub-testers: initial defect sub-tester, non-conductive penetration sub-tester and conductive penetration sub-tester. The initial defect threshold 3, the non-conductive penetration threshold 5 and the conductive penetration threshold 4 are formed to detect initial defect, non-conductive penetration and conductive penetration, respectively.

When the tester starts, it first measures the initial G_t and C_t. The initial defect sub-tester compares the initial G_t with the initial defect threshold 3 to determine whether the initial G exceeds the threshold 3. If no initial G_t

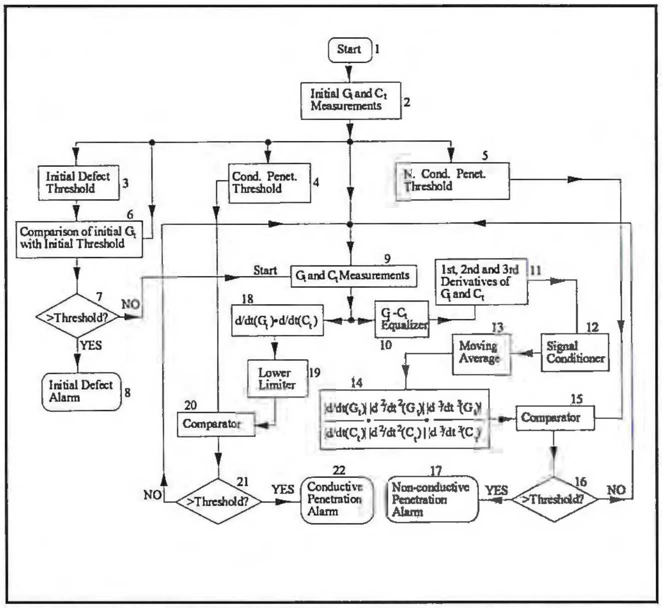

FIGURE 4

Block diagram of the new glove tester.

exceeds the threshold 3, the testing of non-conductive and conductive penetration starts; otherwise, the initial defect alarm 8 is activated. Although the initial defect belongs to non-conductive penetration, the initial defect sub-tester cannot be substituted by non-conductive penetration sub-tester. The non-conductive penetration sub-tester composed of time derivatives of G_t and C_t is insensitive to the slow variation of initial G_t caused by the initial defect.

When there is no initial defect, the tester continues to measure glove conductance G_t and capacitance C_t. The non-conductive penetration sub-tester uses the conditioned Multi-Ratio penetration indicator as its penetration indicator. At the input of the conditioned Multi-Ratio indicator, the C_t is multiplied by an initially determined constant to be near the level of G_t in the G_t-C_t equalizer 10, in order to compress the dynamic range of the indicator during hydration and glove movement. The G_t and equalized C_t are differentiated in block 11 to produce first-, second-, and third-order time derivatives of G_t and C_t. The time derivatives are absolute-valued and their lower values are limited by a pre-set level in the signal conditioner 12. The purpose of limiting the lower value signal is to further limit the dynamic range of the time derivatives. The dynamic-range-limited derivatives are moving-averaged in the moving average 13, in order to reduce the de-synchronization of G_t derivatives with C_t derivatives caused by the nonlinear relationships of G_t to C_t in glove movement in conductive solution (Zeng, 1996). Finally, the magnitude of the non-conductive penetration indicator 14, which is the conditioned $|d/dt(G_t) \cdot d^2/dt^2(G_t) \cdot d^3/dt^3(G_t)| \,/\, |d/dt(C_t) \cdot d^2/dt^2(C_t) \cdot d^3/dt^3(C_t)|$, is compared with the non-conductive penetration threshold 5 in the comparator 15. If the magnitude of the indicator 14 exceeds the threshold 5, the non-conductive penetration alarm 17 is activated, otherwise the above procedure is repeated until a non-conductive penetration is detected.

The conductive penetration sub-tester works similar to the non-conductive penetration sub-tester, except that the conductive penetration sub-tester is simpler. The sub-tester uses the conditioned Product indicator as its penetration indicator. The conductive penetration indicator 18 is composed of only the product of the first-order time derivatives of G_t and C_t. The lower value of $d/dt(G_t) \cdot d/dt(C_t)$ from the indicator 18 is limited by the lower limiter 19 to compress the dynamic range of the indicator. When the magnitude of the conditioned Product indicator exceeds the conductive penetration threshold 4, the conductive penetration alarm 22 is activated, otherwise this procedure is repeated until a conductive penetration is detected.

EXPERIMENTAL SETUP

In the experiment, the block diagram of the proposed glove tester was realized by both hardware and software. The initial and following G_t and C_t were measured by a Solartron SI 1260 impedance/gain-phase analyzer (blocks 1, 2 and 9 in Fig. 4). The collected digital data were then transferred via a General Purpose Interface Bus (GPIB) to the hard disk of a Pentium microprocessor-based personal computer for signal processing. A virtual glove tester (called the "new tester" in the following) was constructed by a MATLAB computing program to realize blocks 3-8 and 11-22 in Fig. 4. For comparison, three other virtual glove testers — the conductance tester, the derivative tester, and the Q tester — using the conductance indicator G_t, the derivative indicator $d/dt(G_t)$, and the Q indicator $\omega C_t/G_t$ as their penetration indicator, respectively, were also constructed by a MATLAB program. These four virtual glove testers processed the same G_t and C_t data files collected by the SI 1260 analyzer.

The experimental set up is shown in Fig. 5. In the test, a glove was filled with 300 ml of 0.9% NaCl solution (inner solution), and suspended from a PVC ring. The ring was hung by a string linked up with a step motor pulley. The step motor was computer controlled to immerse the glove in a 3,200 ml 0.9% NaCl solution (outer solution) in a beaker. Each of two stainless steel electrodes were inserted into inner and outer solutions. The electrodes were connected with the input of the SI 1260 analyzer. The SI 1260 was set to "recycle" mode for continuous data collecting. The "generator" parameters of the analyzer were chosen as: Type = Voltage; Voltage Amplitude = 1.0 volt; Voltage Bias = 0 volt; and Frequency = 10.0 kHz.

The source frequency selection was based on the following considerations. If the frequency were set too low, it would be difficult to design a glove tester to accurately measure C_t. If the frequency were set too high, the intact G_t

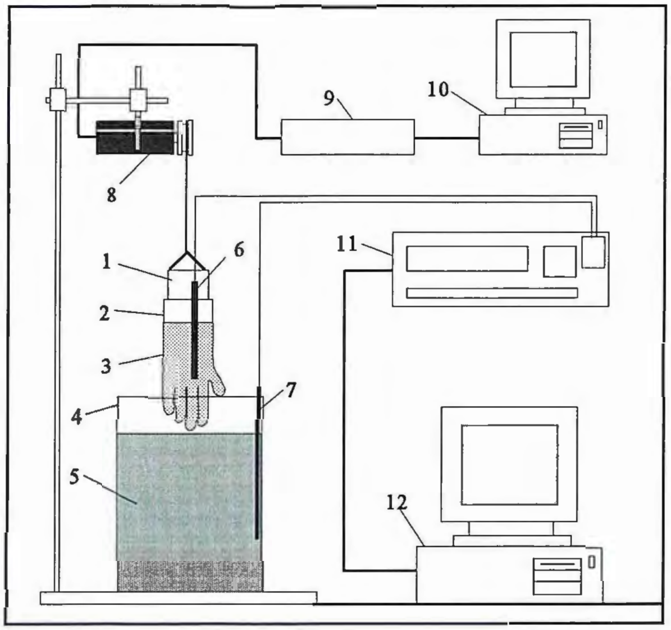

FIGURE 5

Experimental setup.
1: PVC ring;
2: protective glove;
3: inner solution;
4: beaker;
5: outer solution:
6: electrode;
7: electrode;
8: stepper motor;
9: stepper motor control;
10: motor control computer;
11: SI 1260 impedance analyzer
12. data processing computer

(G_t is directly related to measuring frequency, see Zeng, 1996) would be too high compared with G_{bnc} in non-conductive penetration, and would, therefore, lower the penetration detection sensitivity. More consideration should be given to nitrile gloves, which have higher intact G_t than latex gloves and therefore have lower sensitivity and accuracy of penetration detection. It was known from the existing data that the $d/dt(G_t)$ fluctuation of nitrile gloves caused by glove movement is moderate at 10 kHz (Zeng, 1996). The selection of 10 kHz as the source frequency would not only be a good compromise between C_t measurement and higher intact G_t, but would also benefit nitrile glove penetration detection by keeping the glove-movement-caused $d/dt(G_t)$ fluctuation moderate at this frequency.

In the test, a glove was immersed in the outer solution for about 107 seconds so that the glove could have certain degree of membrane hydration. Within the hydration period the glove was moved up and down 1 cm in the outer solution ten times at the moving speed of 0.5 cm/sec., in order to simulate small-magnitude glove movement at slow speed; it was then was lifted totally out of and re-immersed in the solution three times at different speeds: 2.5 cm/sec; 7.7 cm/sec; and 23 cm/sec, in order to simulate maximum-magnitude glove movement in various speeds. The glove G_t and C_t during hydration and glove movements were measured as the noise that would be compared with the G_t and C_t measured during two types of penetrations. After 107 seconds of membrane hydration and glove movement, the glove was penetrated by a rose thorn with maximum thickness of about 600 microns for a non-conductive penetration test, or penetrated by a 150-micron-diameter stainless steel acupuncture needle for conductive penetration test. The total glove conductance G_t and capacitance C_t measured by the SI 1260 analyzer during the test were transferred to and stored on the hard disk of the Pentium computer for off-line data processing through the four virtual glove testers in the MATLAB program.

Eighty gloves were tested in the comparative penetration test, which included equal numbers of four types of gloves: three types of latex medical surgical and examination gloves with low, moderate, and higher membrane hydration rates; and one type of nitrile medical examination gloves. For each 20 pieces of one type of glove, 10 pieces were tested for non-conductive penetration detection and another 10 were tested for conductive penetration detection.

In software penetration detecting sensitivity tests, the sensitivity was defined as a signal-to-noise ratio (*SNR*), where the signal is the maximum magnitude of a penetration indicator during penetration, and the noise is the maximum magnitude of an indicator during membrane hydration or glove movement. The SNR_{hy} refers to the *SNR* whose noise is defined as the maximum magnitude of an indicator during membrane hydration, and SNR_{gm} refers to that during glove movement. As seen from the definition, the higher magnitude of a penetration indicator during penetration, or the lower magnitude of noise, expresses higher penetration detecting sensitivity. In the accuracy tests, the accuracy number was defined as the number of tests in which the $SNR < 1$, i.e., the maximum indicator magnitude during penetration is lower than the maximum noise magnitude of the indicator. The higher the number expressed, the lower the accuracy of the tester.

RESULTS AND DISCUSSION

Glove Impedance Variations in Different Penetrations

Figs. 6 and 7 show two examples of non-conductive and conductive penetrations, respectively. Two latex medical surgical gloves from the same lot were penetrated non-conductively or conductively. As predicted, the variation of C_t is trivial during non-conductive penetration. The variation of C_t during conductive penetration is much greater than that during non-conductive penetration. Table 1 shows the magnitude ratios of penetrated to unpenetrated of the G_t and C_t of the two examples, and their increments ΔG_t and ΔC^t during penetrations. The ratios G_t'/G_t (G_t''/G_t) and C_t'/C_t (C_t''/C_t) refer to the ratios of G_t and C_t during a non-conductive (conductive) penetration to those at

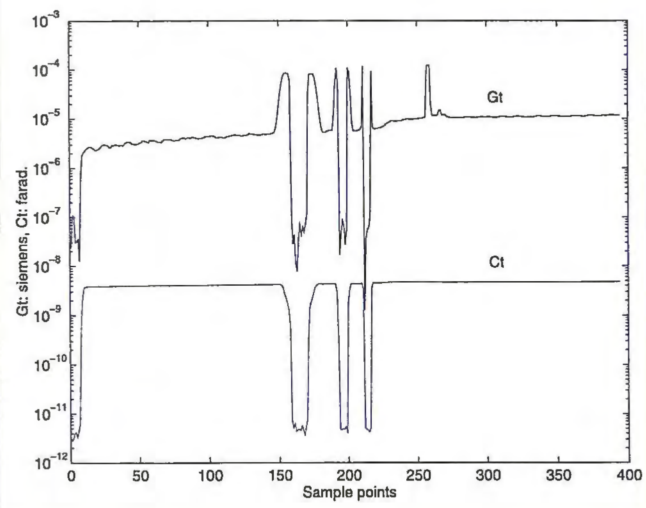

FIGURE 6

Example 1, non-conductive penetration of a latex medical surgical glove.

the nearest undisturbed data point just before the penetration (the tested glove was not moved at this data point), respectively.The C_t'/ C_t is 14 times smaller than the C_t''/ C_t, due to the trivial capacitance variation during non-conductive penetration mentioned above.The G_t''/ G_t is 110 times greater than the G_t'/ G_t, due to the short circuit of the glove impedance by conductive material in conductive penetration.Table 1 also shows that the ratio indicator $|\Delta G_t / \Delta C_t|$ performs better in non-conductive penetration, and the product indicator $|\Delta G_t \bullet \Delta C_t|$ performs better in conductive penetrations, where ΔG_t and ΔC_t are the increments of G_t and C_t during penetrations.Table 2 statistically verifies the above phenomenon. It shows the mean of the above parameters of 40 gloves in non-conductive or conductive penetrations.Attributed to the distinct characteristics of ΔC_t in different types of penetrations, the ratio indicator is more effective in non-conductive penetration, and the product indicator is more effective in conductive penetration.

Comparative Tests

The penetration-detecting sensitivities were compared among these four virtual glove testers. Figs. 8 and 9 are the magnitudes of the five penetration indicators when processing the G_t and C_t data in non-conductive penetration in Fig. 6 and in the conductive penetration in Fig. 7, respectively. It can been seen that the Multi-Ratio indicator has the highest *SNRs* in the non-conductive penetration (see Fig. 8) and the Product indicator has the highest *SNRs* in conductive penetration (see Fig. 9). Table 3 shows the $SNR_{by}s$ and the $SNR_{gm}s$ of the five penetration indicators in these two examples. Figs. 10 and 11 illustrate the third example, which is the non-conductive penetration of a nitrile medical examination glove in conductive solution. It is in an rather difficult test in which the increment of G_t of a nitrile glove during non-conductive penetration ($1.67x10^{-4}$ siemens) is very small compared with its magnitude just before the penetration ($3.91x10^{-4}$ siemens). Even worse, the G_t maximum during penetration ($5.57x10^{-4}$ siemens) is smaller than that in glove movement ($6.36x\ 10^{-4}$ siemens). It is impossible for the three published indicators to distinguish the penetration from the glove movement due to their smaller-than-one $SNR_{gm}s$.The conductive indicator and the

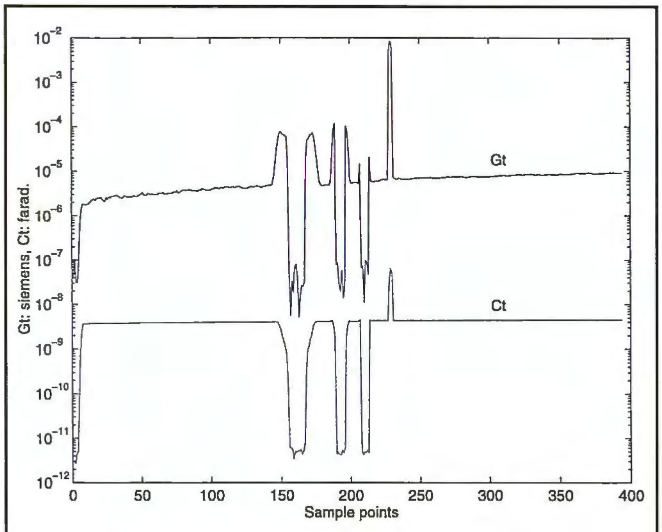

FIGURE 7

Example 2, conductive penetration of a latex medical surgical glove.

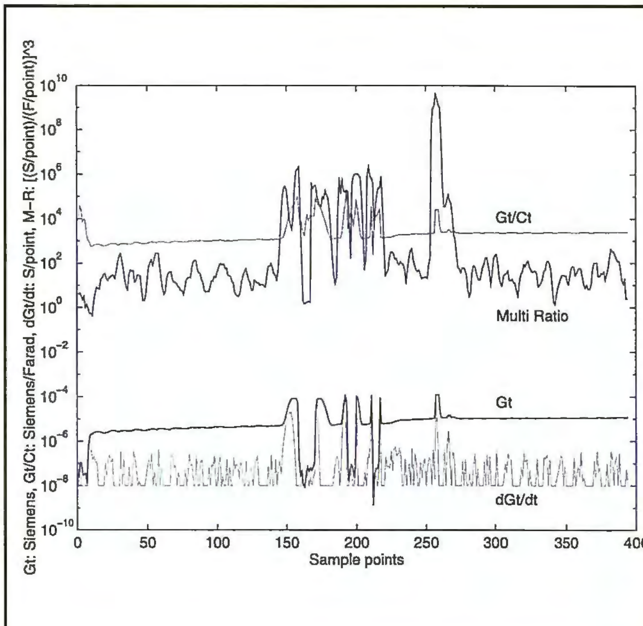

FIGURE 8

Magnitudes of the five penetration indicators in Example 1. The $d/dt(G_t)$ is lower, limited to 10^{-8} siemens/point to yield a clearer plotting.

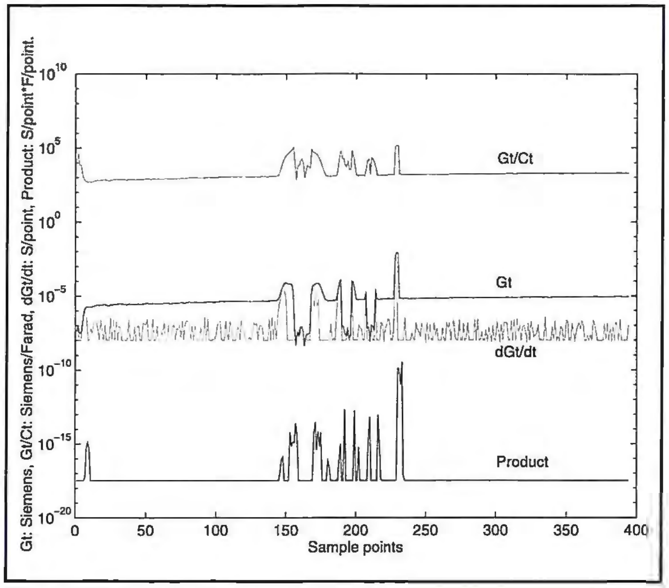

FIGURE 9

Magnitudes of the five penetration indicators in Example 2. The *d/dt(G_t)* is lower, limited to 10^{-8} siemens/point.

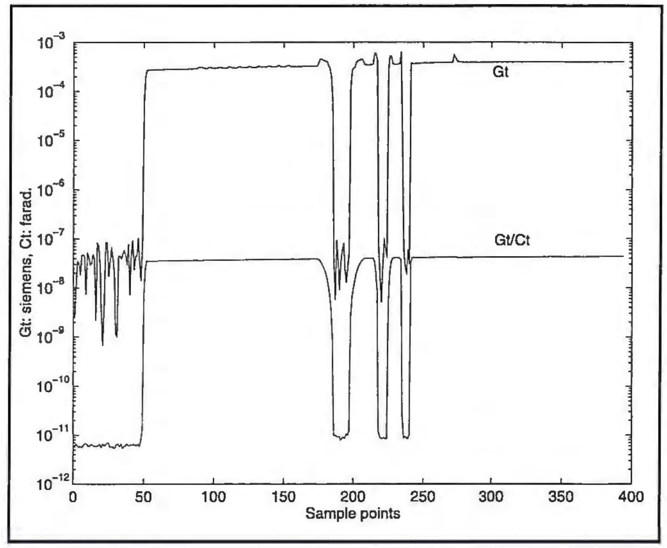

FIGURE 10

Examle 3, non-conductive penetration of a nitrile medical examination glove.

Q indicator also have difficulty distinguishing the penetration from hydration due to their small $SNR_{by}s$ (<1.5). In contrast, the Multi-Ratio indicator of the new tester can easily distinguish the penetration from both membrane hydration and glove movement, due to its higher SNR_{by} (2,309 times higher than the second highest SNR_{by}) and SNR_{gm} (832). The $SNR_{by}s$ and $SNR_{gm}s$ of the four penetration indicators in this test are shown in Table 3 (Example 3).

Tables 4 and 5 show the mean signal-to-noise ratios $SNR_{by}s$ and $SNR_{gm}s$ of 80 glove tests, respectively (40 in non-conductive penetration tests and 40 in conductive penetration tests). Each group contained an equal number of four types of gloves mentioned above. The SNR_{by} in Table 4 indicates that all four testers can detect penetrations from this short period of membrane hydration noise. None of the testers have any $SNR_{by}s$ <1, but the indicators of the new tester have much higher $SNR_{by}s$ in both non-conductive and conductive penetrations. The mean SNR_{by} of the Multi-ratio indicator of the new tester is 3.28×10^{6}-times higher than that of the second best indicator — the derivative indicator — in non-conductive penetration. The mean SNR_{by} of the Product indicator of the new tester is 8.59×10^{4}-times higher than the second best indicator — the conductance indicator — in conductive penetration. These higher $SNR_{by}s$ imply that the new tester can tolerate longer periods of membrane hydration in both types of penetrations than the other mentioned testers.

Table 5 shows that the testers are less immune to glove movements, which cause relatively greater magnitude fluctuation of the five penetration indicators. For the three published penetration testers, the glove movement in non-conductive penetration causes worse $SNR_{gm}s$ than in conductive penetration. Unlike the SNR_{by}, there are a number of smaller-than-one $SNR_{gm}s$ of the first three testers as shown in Table 6. In contrast, the new tester has much higher $SNR_{gm}s$ in both non-conductive penetration (1.9×10^{5}) and conductive penetration (1.2×10^{3}). These

TABLE 1

Variations of G_t and C_t of two latex gloves in non-conductive and conductive penetrations

Example 1: N. Conductive Penetration	G_t'/G_t	C_t'/C_t	$\|\Delta G_t\|$	$\|\Delta C_t\|$	$\|\Delta G_t/\Delta C_t\|$	$\|\Delta G_t.\Delta C_t\|$
	1.15×10^{1}	9.87×10^{-1}	1.12×10^{-4}	6.20×10^{-11}	1.81×10^{6}	6.95×10^{-15}
Example 2: Conductive Penetration	G_t''/G_t	C_t''/C_t	$\|\Delta G_t\|$	$\|\Delta C_t\|$	$\|\Delta G_t/\Delta C_t\|$	$\|\Delta G_t.\Delta C_t\|$
	1.28×10^{3}	1.41×10^{1}	8.31×10^{-3}	5.69×10^{-8}	1.46×10^{5}	4.72×10^{-10}

TABLE 2

Characteristics of G_t and C_t in non-conductive and conductive penetrations.

N. Conductive Penetration (*Mean of 40 gloves*)	G_t'/G_t	C_t'/C_t	$\|\Delta G_t\|$	$\|\Delta C_t\|$	$\|\Delta G_t/\Delta C_t\|$	$\|\Delta G_t.\Delta C_t\|$
	1.73×10^{1}	9.98×10^{-1}	3.94×10^{-4}	1.26×10^{-10}	2.25×10^{7}	5.85×10^{-14}
Conductive Penetration (*Mean of 40 gloves*)	G_t''/G_t	C_t''/C_t	$\|\Delta G_t\|$	$\|\Delta C_t\|$	$\|\Delta G_t/\Delta C_t\|$	$\|\Delta G_t.\Delta C_t\|$
	7.37×10^{2}	9.86×10^{0}	1.14×10^{-2}	6.31×10^{-8}	1.87×10^{5}	7.66×10^{-10}

TABLE 3

SNRs of three test examples in non-conductive and conductive penetrations.

SNR		G_t	$G_t/\omega C_t$	$d/dt(G_t)$	*M-Ratio (n. cnd.) or Product (cnd.)*
SNR_{hy}	Example 1 *(latex, n. cnd. penetration)*	12.84	13.62	30.34	9.28×10^6
	Example 2 *(latex, cnd. penetration)*	1.38×10^3	1.08×10^2	1.03×10^2	4.01×10^7
	Example 3 *(nitrile, n. cnd. penetration)*	1.42	1.43	11.97	2.76×10^4
SNR_{gm}	Example 1 *(latex, n. cnd. penetration)*	1.04	0.16	0.98	1.91×10^3
	Example 2 *(latex, cnd. penetration)*	73.83	1.44	46.08	6.26×10^2
	Example 3 *(nitrile, n. cnd. penetration)*	0.87	0.05	0.60	8.32×10^2

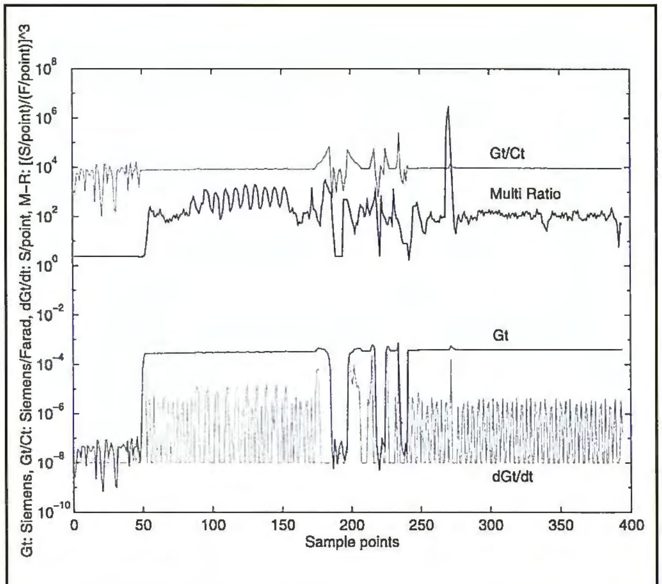

FIGURE 11

Magnitudes of the five penetration indicators in Example 3. The *$d/dt(G_t)$* is lower, limited to 10^{-8} siemens/point.

higher SNR_{gm}s indicate that the new tester has higher penetration-detecting sensitivity than other testers. The new tester had no smaller-than-one SNR_{gm}s in all 80 non-conductive and conductive penetration tests. This proves that the new tester has higher penetration-detecting accuracy than other testers.

CONCLUSIONS

The protective glove conductance G_t and capacitance C_t have distinct characteristics between non-conductive and conductive penetrations, which can be used to construct new penetration indicators to enhance penetration sensitivity and accuracy in both penetrations. Under the test conditions, the Multi-Ratio penetration indicator of the new tester used to detect non-conductive penetration has higher magnitude ratio of penetration to membrane hydration than other known penetration indicators, and has higher immunity to magnitude fluctuation caused by glove movement. The Product penetration indicator of the new tester has similar advantages in conductive penetration detection.

TABLE 4

Magnitude ratio of penetration to membrane hydration of five indicators.

SNR_{hy}	G_t	$G_t/\omega C_t$	$d/dt(G_t)$	*M-Ratio (n. cnd.) or Product (cnd.)*
N. Conductive penetration *(mean of 40 gloves)*	21.46	21.20	39.30	1.29×10^8
Conductive penetration *(mean of 40 gloves)*	810.59	76.14	138.09	6.96×10^7

TABLE 5

Magnitude ratio of penetration to glove movement of five indicators.

SNR_{gm}	G_t	$G_t/\omega C_t$	$d/dt(G_t)$	*M-Ratio (n. cnd.) or Product (cnd.)*
N. Conductive penetration *(mean of 40 gloves)*	3.01	0.69	2.13	1.90×10^5
Conductive penetration *(mean of 40 gloves)*	89.75	5.74	80.21	1.21×10^3

TABLE 6

Number of tests with SNR_{gm}<1.

Number of tests with $SNR_{gm} < 1$	G_t	$G_t/\omega C_t$	$d/dt(G_t)$	*M-Ratio (n. cnd.) or Product (cnd.)*
N. Conductive penetration *(40 gloves)*	6	38	12	0
Conductive penetration *(40 gloves)*	0	11	0	0

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