Analysis of human perception of ELF electric field

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Abstract: For the study of biological effects of ELF electric field, a theoretical and experimental study has been conducted on the human perception of ELF electric field. The electric force exerted on a hair and the hair movement in the field exposure were formulated. They explain the variation of the perception threshold according to a seasonal, a gender and an individual differences. The reasonability of these explanations was confirmed in measurements.

Key words: ELF electric field, Safety standard, Human effect, Detection threshold, Dielectric constant of hair

1. Introduction

The biological effects of ELF electric field have been studied extensively, and the safety standards have been established [1-2]. However, many important points concerning the biological effects of ELF electric fields, such as threshold and mechanism, remain unknown.

Among several possible mechanisms, there is a mechanism to produce apparent biological effects [3]. This mechanism is the stimulation of neural receptors at the surface of the skin [4]. In an electric field, an electric force is exerted on body hair, which causes hair movement and the sensation. In Japan, the safety standard for the field exposure was determined based on the perception threshold. The threshold values of field perception have been investigated and different values have been reported [5-7].

Considering the importance of this problem, we have investigated the cause of this variation in field perception [8-9]. Here we summarize our study on the human perception of ELF electric field.

2. Measurement of field perception

Figure 1 illustrates the measurement of the perception threshold of ELF electric field. An electric field is exposed to a part of the forearm with the plane parallel electrodes (100mm square, 20mm distance). There is a circular hole (30 mmϕ) in the center of the bottom electrode and an electric field is exposed to the body surface through the hole. The detail of the measurement can be found elsewhere [8].

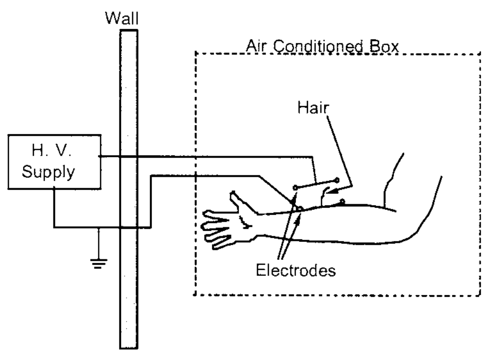

Fig.1 System for measurement of human perception threshold.

3. Various dependence of perception

In the measurement of the perception threshold, we have found various dependences of the field perception. The threshold varied according to the season, the gender of a subject and the individual differences.

Figs. 2 and 3 show these variations. The error bar on the top of a bar graph shows a standard deviation. As shown in Fig.2, the threshold did not appear to be dependent on temperature, but was apparently dependent on the relative humidity (RH) of ambient air. There was not much difference between the positive and the negative DC field exposures. As the relative humidity increased from 50% to 90%, the threshold decreased by almost 30%. This result clearly indicates that the effect of relative humidity can not be neglected when considering the biological effects of an electric field.

Fig.3 shows the dependence of perception threshold on various conditions. Fig.3 (a) shows the experimental conditions. Case-I is a natural hair condition without any treatment to the hair. The hair length of the subjects was 15 to 17mm and the distance between hairs (inversely corresponds to the hair density) was

2.8 to 3.1mm. In case-II, the hair was cut to half its original length. In case-III, half of the hair was extracted, making the distance between hairs twice as large. In case-IV, both treatments (cutting and extraction) were performed on the hair.

Fig.3 (b) shows distinct changes in the threshold due to the changes in the relative humidity from 50% to 90%. The wave-shape top of the bar graph indicates that the subjects did not perceive the field even with the maximum electric field (450 kV/m) available with our system. This result shows that the effect of relative humidity is predominant over other factors. Although the effects were not as clear as that of humidity, lower thresholds were also observed with longer and denser hair.

Although it was difficult to find any statistically significant difference in gender, it seemed that the female threshold is generally higher than the male threshold and that the female threshold becomes lower than the male threshold in the case of short hair (case-IV). This indicates that the effect of the hair condition is generally larger than the effect of gender difference. In the case of short and less hair (case-IV), the female threshold was significantly lower than the male threshold.

This result implies that without the effect of body hair, a female subject is originally more sensitive to a weak sensation on the skin than a male subject. This greater female sensitivity is also known to exist in electric current sensation. This result also shows that the effect of body hair on sensitivity is predominant over gender difference. Therefore, more attention should be paid to the condition of body hair when considering the individual variability in field perception.

To clarify the cause of these variations, we need to know the mechanism of the field perception. Fig.4 shows the result of the experiment to show the typical mechanism. When we shaved off the body hair of the forearm, we could not perceive the field up to 450kV/m which was the maximum limit of our experimental system. This shows that the body hair plays an important role in the field perception.

When a field is exposed to our body, an electric force is exerted on the body hair. The hair moves and stimulates the neural receptors at the surface of the skin. This causes the sensation and we perceive an electric field. Therefore, the above variations in the perception threshold can be explained in the analysis of the electric force and the movement of the hair.

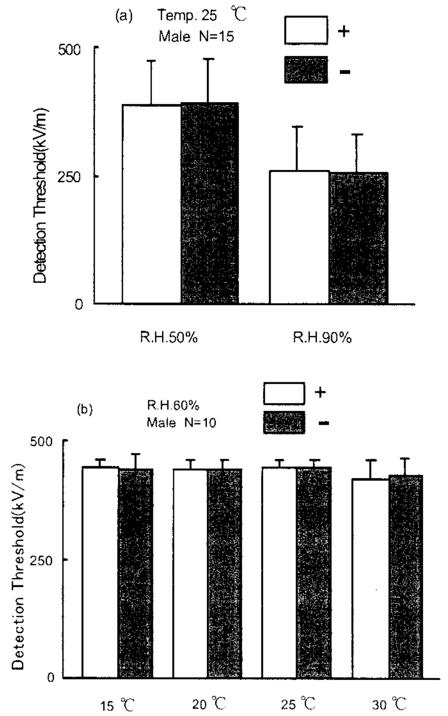

Fig.2 Measurement of perception threshold of electric field (subjects age:21-24years; + - indicate the polarity of upper electrode): (a)dependence on relative humidity, (b)dependence on temperature.

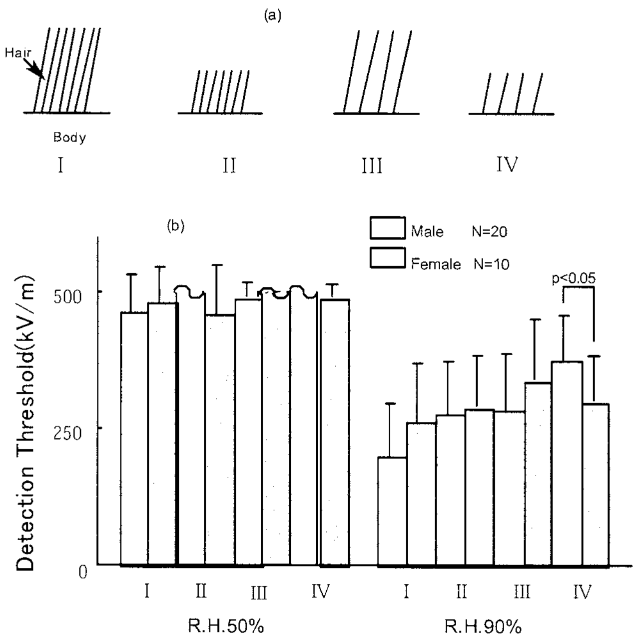

Fig.3 Dependence of perception threshold on various conditions (subjects age: 20-25 years): (a) conditions of body hair, (b) measured thresholds.

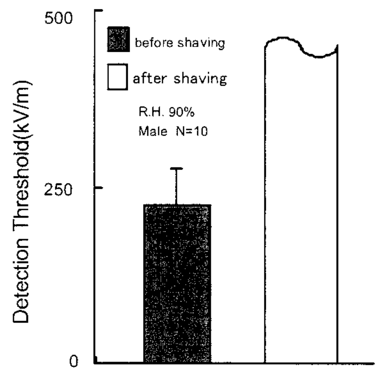

Fig.4 Perception threshold before and after shaving treatment (subjects age:21-23years).

4. Electric force and hair movement

For a theoretical analysis, a hair on the body surface is modeled as shown in Fig.5. A dielectric cylinder is standing obliquely (with its axis of rotation in a vertical plane) on a horizontal conductor plane. The permittivity of the cylinder is $\varepsilon_0\varepsilon_r$ where ε_0 is the permittivity of vacuum and ε_r is the dielectric constant of hair. The parameter θ is the angle of the axis in the vertical plane.

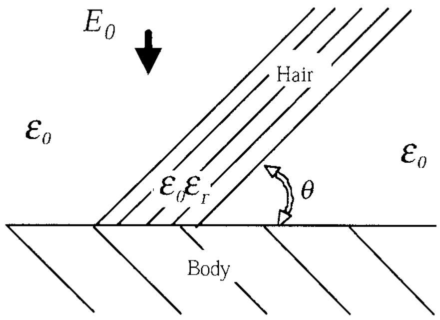

Fig.5 Theoretical model of body hair in E field.

The force applied on a hair is the total sum of the force components exerted along the surface of the hair. First, let us consider a small cross sectional cut of a hair with a thickness *dl* as shown in Fig.6. The total force *F* is given as,

$$F(\theta) = \int_0^L d\ell \int_0^{2\pi} r d\varphi f(\theta,\ell,\varphi)\cos\varphi \qquad (1)$$

where *L, dl, r,* φ, $f(\theta,l,\varphi)$ are the length along a hair, the length of the volume element (the small cross sectional cut), the radius of the hair, the angle measured from the sagittal plane and the electric force at hair surface, respectively.

The total force is obtained by the vector sum of the electric force exerted at the interface of the dielectric discontinuity. The electric force exerted on the small unit area of hair surface $f(\theta,l,\varphi)$ is given by [10],

$$f(\theta,\ell,\varphi) = \frac{\varepsilon_0}{2}(\varepsilon_r - 1)(\sin^2\theta + \frac{1}{\varepsilon_r}\cos^2\theta)E^2(\theta,\ell,\varphi) \qquad (2)$$

where $E(\theta,l,\varphi)$ is the electric field at hair surface.

Considering the cylindrical symmetry, this equation can be approximated in the following two conditions, i.e.

$$F(\theta) \approx \frac{1}{2}\varepsilon_0\varepsilon_r \sin^2\theta(E_a^2 - E_b^2) r d\ell \qquad \theta >> 0 \qquad (3),$$

$$F(\theta) \approx \frac{1}{2}\varepsilon_0 \cos^2\theta(E_a^2 - E_b^2) r d\ell \qquad \theta \approx 0 \qquad (4),$$

where Ea and Eb are the electric fields at the top and the bottom parts of the hair cross-section. The difference between E_a and E_b increases as ε_r increases. Therefore, Eqs. (3) and (4) show that the electric force increases as the dielectric constant of the hair increases.

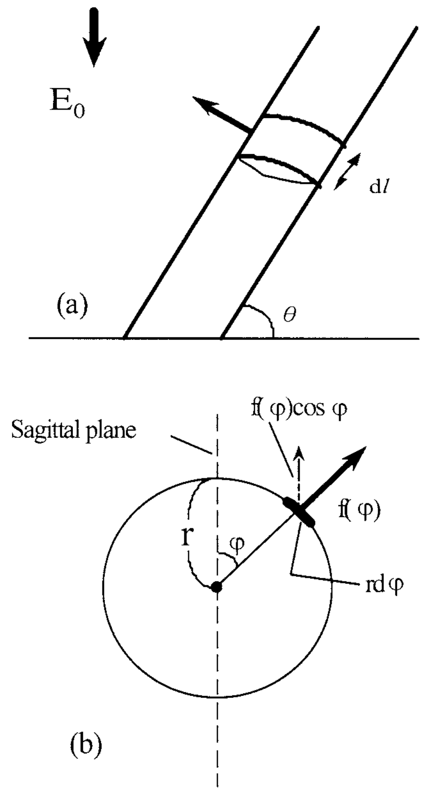

Fig.6 Principle of calculation of electric force on a hair ;
(a) integration along axial direction,
(b) integration along peripheral direction.

To analyze the movement of a hair, we modeled a hair as an elastic rod sticking out obliquely from a visco-elastic bed of a skin tissue as shown in Fig.7. The deflection of the hair is given by [10],

$$y = \frac{1}{EI}(k_5 x^5 + k_4 x^4 + k_3 x^3 + k_2 x^2 + k_1 x + k_0)$$

$$k_5=\frac{f_2-f_1}{120L_a},\quad k_4=\frac{f_1}{24},\quad k_3=-\frac{f_1+f_2}{12}L_a,\quad k_2=\frac{f_1+2f_2}{12}L_a^2$$

$$k_1=\frac{f_1+f_2}{4}L_aL_b^2+\frac{f_1+2f_2}{6}L_a^2L_b,\quad k_0=\frac{f_1+f_2}{6}L_aL_b^3+\frac{f_1+2f_2}{12}L_a^2L_b^2 \quad (5),$$

where E and I are the Young's modulus and the moment of inertia of area for the hair. f_1 and f_2 are the values of the distributed force at the bottom and the top ends of the hair. L_a and L_b are the lengths above and below the surface, respectively.

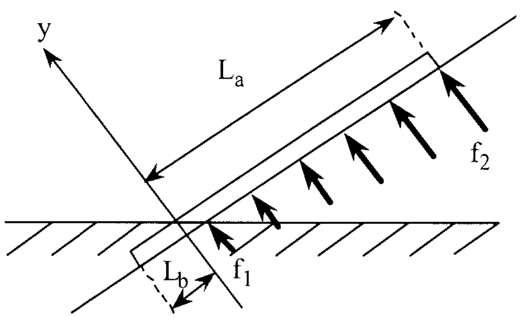

Fig.7 Distributed force along the hair above body surface.

5. Analysis of threshold variation

The reasonability of the derived equations (3)-(5) was confirmed in respective experiments [8-10]. Through these analyses, we could establish the chain of the causes for the variation of the field perception.

When the relative humidity (RH) around the hair increases from 50% to 90%, the relative dielectric constant of the hair increases approximately from 10 to 80 [8]. The increase in the dielectric constant of the hair results in the increase in the electric force exerted on the hair. The increase in the force causes the increase in the amount of hair movement. Finally, in high humidity, the hair moves more and the perception threshold becomes less than the case in lower humidity. It was shown theoretically and experimentally that the change in the RH from 50% to 90% causes distinct visible change in hair movement and significant change in perception threshold [9].

According to the same cause-effect relationship, the variation of perception threshold among different individuals can be explained. The subject with dense and long hair shows lower perception threshold, or he/she is more sensitive to an electric field than the subject with less and shorter body hair. This explains the difference of the perception between male and female subjects, as well. In general, male subjects showed lower perception threshold than female subjects. However, when we make the hair conditions same between male and female subjects by trimming and thinning the hair, the female subjects showed lower threshold [9]. This shows the intrinsic sensitivity of female subject and the dominance of the effect of body hair over the sensitivity difference.

6. Conclusion

The stimulation at body surface is one of the clear effects of ELF electric field. It was shown that we perceive the field by the movement of body hair. The variation in the perception threshold due to the humidity, the gender and the individual differences were shown. The movement of hair caused by electric field exposure was analyzed theoretically and experimentally. The force and the movement of the hair were formulated. Based on this formulation and additional experimental study, the cause-effect relationships for the above variations were clarified.

These results are useful not only for the clarification but also for establishing appropriate safety standards for each country with different climate and for each nation with different body conditions.

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