Fundamental Study on Body Hair Movement in ELF Electric Field Exposure

Hisae O. Shimizu and Koichi Shimizu*
Department of Clinical and Rehabilitation Engineering,
Hokkaido Institute of Technology, Sapporo, 006-8585 Japan.
shimizu@hit.ac.jp
** Graduate School of Information Science and Technology,*
Hokkaido University, Sapporo, 060-0814 Japan.
shimizu@bme.eng.hokudai.ac.jp

***Abstract* – To investigate the perception of ELF electric field, a fundamental study was conducted on the movement of body hair in field exposure. The electric force exerted on a hair was given from the force component at dielectric discontinuity. With this force, the equation of the hair displacement in field exposure was derived. The displacement evaluated by the equation agreed well with experimental results. Finally, the hair movement in field exposure was formulated theoretically. The derived equation well describes the real movement of body hair in field exposure. In this analysis, the mechanisms of the threshold variation in the field perception was made clear.**

I. 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 report theoretical and experimental study on the movement of the body hair in ELF electric field exposure.

II. Electric Force on Body Hair

For a theoretical analysis, a hair on the body surface is modeled as shown in Fig.1. 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.

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.2. 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.

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

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

where E_a and E_b 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.

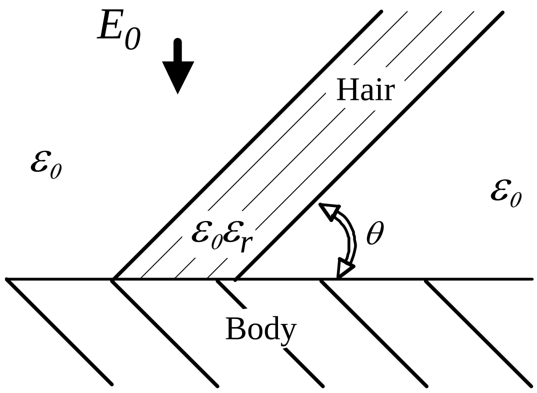

Fig.1. Theoretical model of body hair in E field.

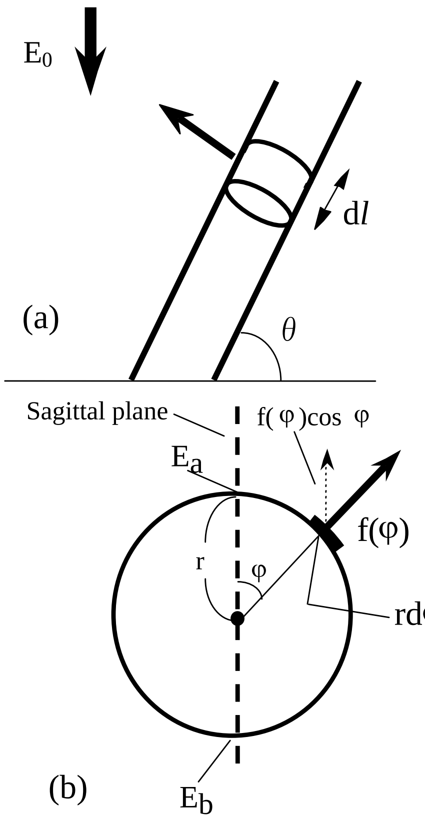

Fig.2. Principle of calculation of electric force on a hair ;
(a) integration along axial direction,
(b) integration along peripheral direction.

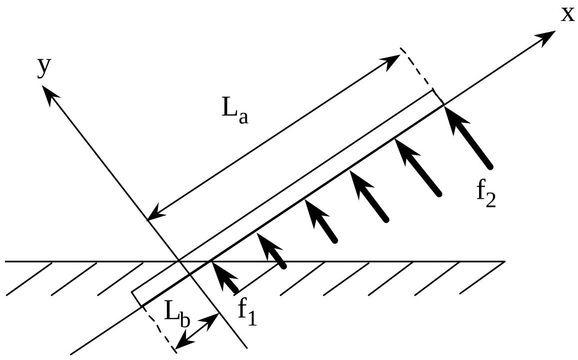

Fig.3. Distributed force along the hair above body surface.

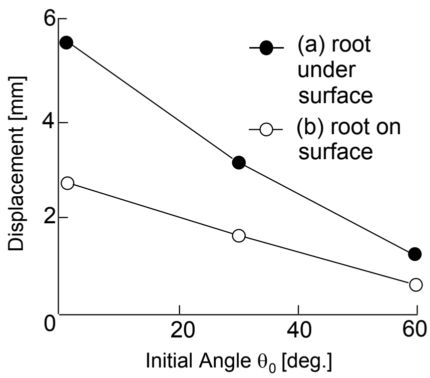

Fig. 4. Estimation of hair displacement.

III. Displacement of Hair in Field Exposure

It is clear that the movement of the body hair plays the key role to cause the perception of the electric field exposed to the outside of the body. Therefore, to study the perception threshold, it is necessary to examine the movement of the body hair by the electric force derived above. As the first step, we have evaluated the displacement of a hair in field exposure to find out whether the hair moves over sensible distance or not.

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.3. The deflection of the hair is given by [10],

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

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

$$k_2 = \frac{f_1 + 2 f_2}{12} L_a^{\,2},$$

$$k_1 = \frac{f_1 + f_2}{4} L_a L_b^{\,2} + \frac{f_1 + 2 f_2}{6} L_a^{\,2} L_b,$$

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

where E and I are the Young's modulus and the moment of inertia 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 hair lengths above and below the surface, respectively.

Fig. 4 shows the displacement with different initial angle of the hair. To estimate the effect of the resistance caused by the part under the skin surface, the displacements for the two extreme cases (zero and infinite resistance in the body) were evaluated. The true displacement should exist between these two cases. In this result, we found that the horizontal hair is raised up several millimeters. This agreed well with experimental results.

Through this study, it became clear that the study of the electric force exerted on the hair is not sufficient. For the analysis of perception threshold, we have to study the hair movement in field exposure.

IV. Hair Movement in Field Exposure

To analyze the movement of a thin object such as a hair, we have to take the air viscosity into account. The equation for the angular movement of a column is given by,

$$\ddot{\theta} + \frac{R}{m_h}\dot{\theta} + \frac{f}{m_h \delta_{\max}}\theta = \frac{3f}{2m_h L} \qquad (6),$$

where θ, R, m_h, f, δ_{max} and L are the angle of the hair column, the mechanical resistance coefficient of a column moving in viscous fluid, the mass of body hair of a unit length, the electric force averaged over the hair length, the final displacement of the hair-tip, and the length of the hair over the body surface, respectively. The resistance coefficient R is given by [10],

$$R = \frac{8\pi\mu}{2\left(\ln \frac{8}{R_e} - 0.577\right) + 1} \qquad (7),$$

where μ and R_e are the viscosity(1.81×10^{-5} Ns/m^2) and the Reynold's number, respectively.

The step response of this differential equation is given as the solution for the over-damping case of the second order system,

$$\theta(t) = K\{1 - \frac{\alpha + \sqrt{\alpha^2 - 1}}{2\sqrt{\alpha^2 - 1}} e^{-(\alpha - \sqrt{\alpha^2 - 1})\omega t} + \frac{\alpha - \sqrt{\alpha^2 - 1}}{2\sqrt{\alpha^2 - 1}} e^{-(\alpha + \sqrt{\alpha^2 - 1})\omega t}\} \qquad (8),$$

where $K = \frac{3}{2L}\delta_{\max}$, $\alpha = \frac{R}{2\omega m_h}$, $\omega = \sqrt{\frac{f}{m_h \delta_{\max}}}$.

With practical parameters of a hair, the temporal change of the hair angle in field exposure is obtained [10] as

$$\theta(t) = 21.5(1 - 1.03 e^{-11.2t} + 0.0345 e^{-335t}) \qquad (9).$$

This equation shows that when the step-wise electric field is applied, the hair angle increases exponentially with the time-constant of 0.0893 seconds. This means that a body hair stands up with the time scale of 0.1 seconds which is easily observable with the naked eye. The Eq.(9) can also describe the hair movement when an AC electric field with the frequency of 50 or 60 Hz is applied. The hair stands up with the 0.1 sec time-constant accompanied by the 100 or 120 Hz vibration of a few percent amplitude.

In the study of the field perception under high-voltage power transmission lines, the movements of body hair have been reported [5, 6]. The above mentioned movement estimated by the Eq.(9) agreed well with the movement in these reports.

V. Dependence of Force on Dielectric Constant

We showed above that the hair displacement and the hair movement are directly affected by the electric force exerted on the hair. The electric force is dependent on the dielectric constant as shown in Eq.(2). Therefore, we examined the dependence of the electric force on the dielectric constant of the hair to explore the connection between the humidity and the hair movement.

The electric force distribution along the hair was obtained using the finite element method [10], and the electric force was calculated using Eq.(2). Figure 5 shows the result. The electric force increases almost linearly as the dielectric constant increases. The rate of this increase is common in both cases of small and large initial angle of the hair. However, the magnitude of the electric force is different between these cases. Figure 6 shows the dependence of the force magnitude on the initial angle of the hair. The force decreases as the hair angle approches to perpendicular. These results suggest that strong electric force is exerted on the lying hair and that the force decreases as the hair stands up. The larger force is exerted on the hair with the larger dielectric constant.

VI. Dependence of Hair Movement on Humidity

We have reported that the perception threshold of electric field changes in different humidity. Through theoretical and experimental study, we have shown that with the increase of relative humidity the dielectric constant of body hair and consequently the electric force exerted on the hair increase. To

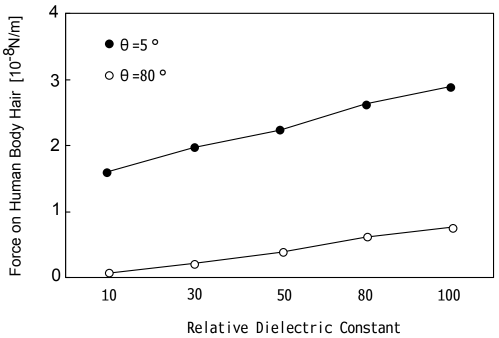

Fig. 5 Dependence of electric force on dielectric constant of body hair.

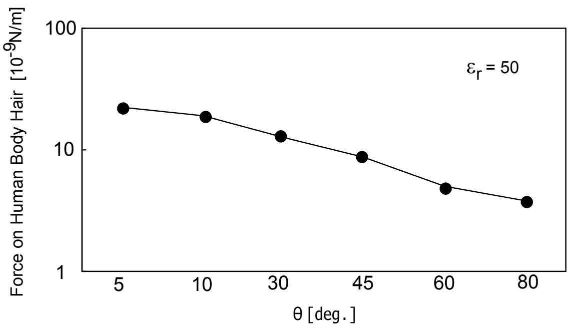

Fig. 6 Dependence of electric force on standing angle of body hair.

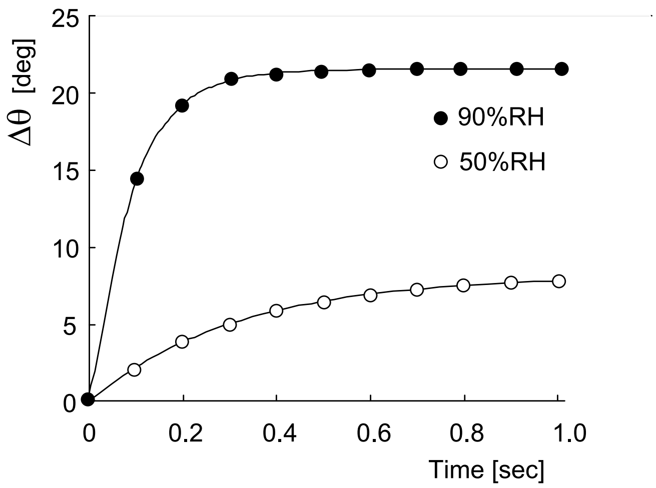

Fig. 7. Temporal change of hair angle for step-wise electric field exposure.

examine the effect of humidity on the field perception, the amount of movement-change due to this force-change was evaluated with the Eq.(7) derived above. Fig.7 shows the difference in the hair movement in different humidity. In the high humidity the hair stands up faster and to larger angle than in the low humidity. This theoretical calculation agreed well with the result of measurement [10].

VII. Conclusions

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 movement of hair caused by electric field exposure was analyzed theoretically and experimentally. The force and the movement of the hair were formulated. The derived equation explained well the real movement of the body hair in field exposure.

The variation of perception threshold in different humidity had been reported. As the mechanism of this variation, we had shown that the electric force exerted on the hair increases with the increase of the relative humidity. In the present study, the sequence of the mechanisms of this threshold variation was made clear. When the humidity increases, the dielectric constant of body hair increases, and consequently the electric force on the hair increases. Then, the amplitude of the hair movement increases and the time-constant of the movement decreases.

These results are useful not only for the analysis of perception threshold 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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