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Skin Cell Death Due to Natural Electric Field

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Abstract

Various electrochemical experimental facts occurring beneath the bottom of the stratum corneum were obtained by the group of M.Denda around the beginning of twentieth century. Their results attracted our attention because of similarities with a phenomena occurring near the surface of ceramic balls in water. For example calcium ions play an important role in both of them. The characteristic phenomenon studied in [Kawarada and Pironneau \(2019\)](#) is the generation of a huge electric field near the surface of the ceramic balls. Then we can predict the existence of a similar electric field in very thin regions below the stratum corneum (SC). If true, the cells approaching the SC undergo necrosis. This is the main idea of this paper. We use the experimental data of Zimmermann et al [Zimmerman et al \(1976\)](#) for the maximum electric field before the breakdown of epidermal cells.

Keywords: Electrochemical phenomenon, Poisson-Boltzmann, apoptosis, necrosis

MSC Classification: 92C40 , 35Q20 , 92B05

Introduction

Interesting phenomena occurs in the outer layer of the skin of mammals, which consists of the stratum corneum (SC) and the living layer of the epidermis. The epidermal cells which are produced at the basal layer go up in the epidermis and arrive near the SC and die there a natural death(apoptosis). This fact is commonly accepted. In this paper we discuss a possibility of a necrosis due to an electrochemical phenomena which occurs just beneath the SC. If true, it gives a electrochemical explanation for the cell's death.

In the paper, by applying the fundamental equations of electrochemistry just beneath the SC – where water and its ions in the epidermis constitute the electrolyte, we show that in a very thin layer there is a huge electric field. Henceforth, when an epidermal cell arrives in that layer, it is destroyed.

In section 1, we recall the experimental facts which state the death of cell as accidental.

In section 2, it is pointed out that the localisation of calcium ions near the bottom of the SC plays an important role to build a huge electric field there. An explicit solution of the Poisson-Boltzmann equation is given to compute the electric field and the electric potential.

Finally, in section 3, we conjecture that inside the human body (or other mammals) various kinds of boundaries like the one between the SC and the epidermis exist. On such boundaries there exists a possibility of the occurrence of the necrosis discussed in this paper, if appropriate conditions hold.

1 Experimental facts

It is a strange observation that cells arriving just below the SC die a natural death. In order to destroy the organization of a cell, the corresponding binding energy is needed. Where would this energy comes from? Some hints to solve the question are found in the following¹.

- A. A hint at the existence of calcium ions beneath the SC with high density is given in [Denda et al \(2014\)](#), [Kobayashi et al \(2016\)](#).
- B. Another hint follows from an interesting experiment by group of M. Denda [Denda et al \(2014\)](#), [Denda and Kumazawa \(1995\)](#), [Kobayashi et al \(2016\)](#). After tearing off the SC by cellophane tape, they paint the surface of skin with an electrolytic macromolecule, an ion-exchange resin and a barium sulfate separately. Then they found that the barrier function of the SC was reinforced by all of them. This fact suggests that three materials play the role of a substitute of the SC. A common point of these materials is that the surface of them is covered with negative ions. In other words, the bottom of SC plays the role of an electrode [N.Komazawa \(2005\)](#), [S.Fujiwara et al \(2004\)](#).
- C. An interesting fact is that if we cover skin by a plastic membrane after tearing it with cellophane tape, the function to reform the SC does not work.

¹Usually it is said that this energy is supplied by ATP [Kobayashi et al \(2016\)](#)

Here, the role of plastic is not to let water through [Denda and Kumazawa \(1995\)](#), [Denda \(2018\)](#), [G.Grubauer et al \(1989\)](#).

- D. Finally we recall an example of electrical breakdown by [M.Hayamizu et al \(1989\)](#). They used the plate-plate electrode system to yeast cells floating in pure water and found $E_0 = 1.6 \cdot 10^6$ (V/m) to be the critical electric field, because the distance between the electrodes is 10mm and 16kV was applied. Then it was observed that many destroyed cells have a rough surface and a pore on it.
- E. The skin acts like the battery. The electric potential between the top and the bottom in the epidermis is about 0.1V [Barker et al \(1982\)](#), [Denda et al \(2014\)](#), [Denda \(2018\)](#).

The facts mentioned above suggest that the bottom of the SC is surrounded with calcium ions and plays the role of an electrode and water in the epidermis constitutes the electrolyte. Then these facts remind us of the same electro-chemical phenomena as occurred near the surface of ceramic ball in natural water studied in [Kawarada and Pironneau \(2019\)](#).

2 Generation of a Huge Electric field

2.1 Diffused electric double layer

The bottom of the SC is also an interface between the SC and the epidermis. Hereafter the interface is denoted the surface. The surface is negatively charged with ions adsorbed from the electrolyte solution and dissociable groups existing at the surface. The surface does not exist nakedly and is surrounded by a cloud of various ions. A lot of calcium ions attracted close to the surface exist in the cloud. Whereas ions with negative charge are driven far away to the outside. In this way an electric double layer is formed. The outside of this double layer looks blurred by a Brownian motion of ions. Then this double layer becomes a diffused electric double layer [Derjaguin and Landau \(2013\)](#). Let us show that a huge electric field appears in this double layer.

2.2 Poisson-Boltzmann equation

Here we analyze how the potential changes in the double layer. Let $z = 2$ be the valence number of Ca_{++} ion, and n the concentration of calcium ion. Take the origin of coordinate x on the lower surface of the SC and let the x -axis be vertical toward the surface. The electric potential ψ is described by a Poisson-Boltzmann equation as follows [Kawarada and Pironneau \(2019\)](#), [Derjaguin and Landau \(2013\)](#).

$$\frac{d^2\psi}{dx^2} = 2 \frac{zen}{\varepsilon_\lambda \varepsilon_0} \sinh\left(\frac{ze\psi}{kT}\right), \quad (0 < x) \quad (1)$$

$$\psi(0) = \psi_0, \quad (2)$$

$$\psi(+\infty) = 0. \quad (3)$$

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Here $\varepsilon_\lambda = 78.5$ is the relative dielectric constant of the electrolyte in water. $\varepsilon_0 = 8.8542 \cdot 10^{-12}$ is the dielectric constant of vacuum.

- $e = 96484/N_A$ is the elementary electric charge.
- $k = 1.381 \cdot 10^{23}$ is Boltzmann constant.
- T is absolute temperature ($T=293$).
- ψ_0 is the boundary value of ψ at $x=0$.

Recall that $n = N_A C$ with $N_A = 6.03 \cdot 10^{23}$, the Avogadro number and $C = 1\text{mol}/m^3$ the concentration [Keener and Sneyd \(2009\)](#). Consequently

$$AC = 2ze \frac{N_A}{\varepsilon_\lambda \varepsilon_0} = 5.5527 \cdot 10^{14} \quad (4)$$

$$b = \frac{ze}{kT} = 79.21. \quad (5)$$

Then we have

$$\frac{d^2\psi}{dx^2} = AC \sinh(b\psi) \quad (6)$$

Multiplying (1) by $d\psi/dx$ and integrating the resulting equation yields

$$\frac{1}{2} \left(\frac{d\psi}{dx} \right)^2 = \frac{AC}{b} \cosh(b\psi) + D, \quad (7)$$

where D is constant. Using the boundary condition at $x = +\infty$, we have

$$\frac{d(b\psi)}{dx} = \pm \sqrt{2ACb (\cosh(b\psi) - 1)} = \pm 2\sqrt{ACb} \sinh \frac{b\psi}{2}. \quad (8)$$

Using hyperbolic-trigonometric identities with $\tanh \frac{b\psi}{4}$, it is easy to show (see [Appendix](#)) that

$$\psi(x) = \frac{4}{b} \tanh^{-1} \left(e^{-x\sqrt{\mu}} \tanh \frac{b\psi_0}{4} \right) \quad \text{with} \quad \mu = ACb \quad (9)$$

Using (1), $\sqrt{\mu} = 0.21 \cdot 10^9 (m^{-1})$ and with $\psi_0 = 0.1$ (see [Barker et al \(1982\)](#)), the potential is

$$\psi(x) = 0.05 \tanh^{-1}(0.9640e^{-0.21x}) \quad \text{where } x \text{ is in nano-meter}$$

The electric field can now be computed as

$$E(x) = \frac{d\psi}{dx}(0) = \frac{2\sqrt{\mu}}{b} \sinh \left(2 \tanh^{-1} \left(e^{-x\sqrt{\mu}} \tanh \frac{b\psi_0}{4} \right) \right), \quad (10)$$

$$= 0.00525 \cdot 10^9 \sinh \left(2 \tanh^{-1}(0.964e^{-0.21x}) \right) \quad (11)$$

Note that $E(0) = 0.14 \cdot 10^9$ and $E(18.4) = 2.21 \cdot 10^5$. The potential ψ and the electric field E are plotted on Figure 1.

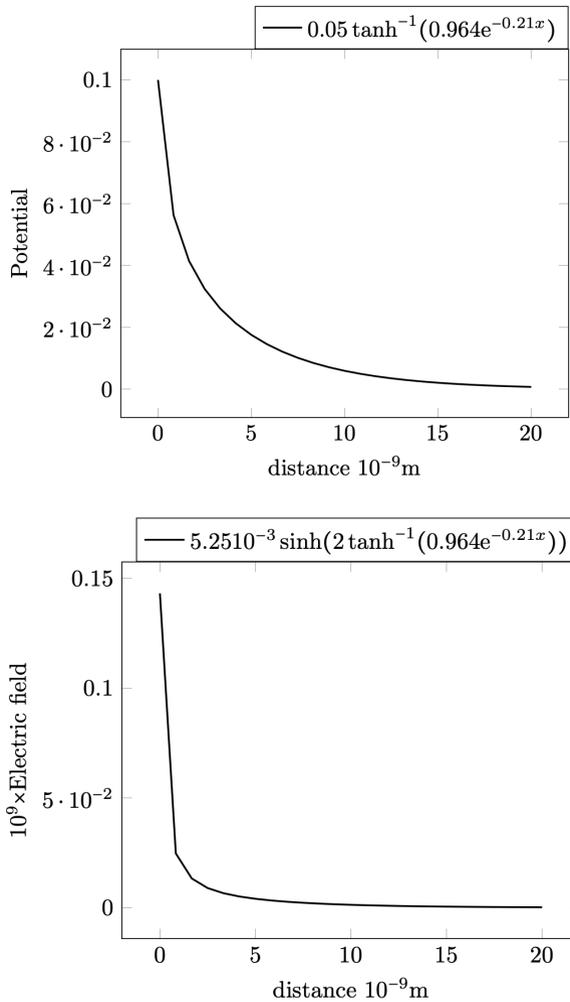


Fig. 1 Potential (top) and $10^{-9} \times$ Electric field (bottom) function of distance from center of cell (in nano meter).

3 Appearance of Necrosis

3.1 Electrochemical model (U.Zimmerman et. al.)

The mechanism of the breakdown of the cell membrane can be explained in terms of an electrochemical model. This model implies that the presence of the

electric field added to the membrane sets up stresses appearing as mechanical compression inside the membrane. When the electric field is applied to the membrane, the electric compressive force can increase more rapidly than the elastic restoring force peculiar to the membrane and with decreasing membrane thickness. An instability appears leading to an electromechanical collapse (the dielectric breakdown) of the cell membrane. The electric field corresponding to the dielectric breakdown is defined as the critical electric field strength (E_0), the value of which is about $2.2 \cdot 10^5$ (V /m), according to [Zimmerman et al \(1976\)](#).

3.2 The mechanism of Necrosis

Referring to the curve of the electric field obtained in the section 2, the thickness of the domain, inside which the electric field is larger than E_0 extends beyond 13.8 nm. This distance is about 3.45 times of the thickness of the membrane. This domain is called the critical domain (the CD). The cell pushed up from below enters into the CD. Then the dielectric breakdown starts. When the upper part of the membrane arrives at the bottom of the SC, a tear may be made near the point of the membrane and then a hole. After the completion of the hole, the contents inside the cell flow outside through the hole. These phenomena are considered to represent the mechanism of necrosis.

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Declarations.

- The authors have no relevant financial or non-financial interests to disclose.
- The authors have no conflicts of interest to declare that are relevant to the content of this article.
- Both authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.
- The authors have no financial or proprietary interests in any material discussed in this article.

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4 Appendix

To solve

$$\frac{d\phi}{dx} = -\sqrt{\mu} \sinh \phi$$

we use the identity

$$\sinh 2\phi = 2 \sinh \phi \cosh \phi = 2 \tanh \phi \cosh^2 \phi = 2 \tanh \phi \frac{\cosh^2 \phi}{\cosh^2 \phi - \sinh^2 \phi} = \frac{2 \tanh \phi}{1 - \tanh^2 \phi}$$

Now

$$\frac{d \tanh \frac{\phi}{2}}{dx} = \frac{1}{2} (1 - \tanh^2 \frac{\phi}{2}) \frac{d\phi}{dx} = -\frac{1}{2} (1 - \tanh^2 \frac{\phi}{2}) \sqrt{\mu} \frac{2 \tanh \frac{\phi}{2}}{1 - \tanh^2 \frac{\phi}{2}} = -\frac{\sqrt{\mu}}{2} \tanh \frac{\phi}{2}$$

Integrate this equation to obtain:

$$\log \frac{\tanh \frac{\phi(x)}{2}}{\tanh \frac{\phi(0)}{2}} = -x\sqrt{\mu} \implies \phi(x) = 2 \tanh^{-1} \left(\tanh \frac{\phi(0)}{2} e^{-x\sqrt{\mu}} \right)$$