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Rising Level of Public Exposure to Mobile Phones: Accumulation through Additivity and Reflectivity

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A dramatic development occurring in our daily life is the increasing use of mobile equipment including mobile phones and wireless access to the Internet. They enable us to access several types of information more easily than in the past. Simultaneously, the density of mobile users is rapidly increasing. When hundreds of mobile phones emit radiation, their total power is found to be comparable to that of a microwave oven or a satellite broadcasting station. Thus, the question arises: what is the public exposure level in an area with many sources of electromagnetic wave emission? We show that this level can reach the reference level for general public exposure (ICNIRP Guideline) in daily life. This is caused by the fundamental properties of electromagnetic field, namely, reflection and additivity. The level of exposure is found to be much higher than that estimated by the conventional framework of analysis that assumes that the level rapidly decreases with the inverse square distance between the source and the affected person. A simple formula for the exposure level is derived by applying energetics to the electromagnetic field. The formula reveals a potential risk of intensive exposure.

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Japan is a country where many people use mobile communicators frequently almost anywhere including in public transport, where access is enabled even in underground trains by base stations placed in tunnels, although their use is prohibited in hospitals and airplanes to prevent possible fatal accidents. On one occasion the author experienced interference from a mobile phone in the headset of a music player, and later found that serious interference also occurred in some hearing aids; such interference occurs even if there is a distance of more than five meters between the source and an affected person. The incidents were not consistent with a well-known paradigm for interference by mobile phones that emphasizes that the interference occurs only if the affected person is sufficiently close to the source. Based on this paradigm, several guidelines have been constructed, one of which recommends, "people should not use mobile phones within 22 centimeters of a person with a cardiac pacemaker."[1)] This *short-range interference paradigm* has been widely accepted as a guidelines in several places and, to our knowledge, it is the only indication to citizens of the possibility of intensive exposure. Extensive studies are also in progress to clarify the effects on the health of mobile users themselves, who are the nearest to the mobiles.[2–4)] Here, we do not discuss this aspect because the users use the mobiles at their own risk. Rather, we focus on the issue of public exposure to emission from anonymous users, because an affected person cannot control or avoid exposure even when a health condition exists. In this sense, the latter is a more serious problem than the former.

The lack of recognition of the possibility of high levels of exposure could be attributed to the lack of a simple theory describing exposure caused by a distributed emission of electromagnetic waves in a reflective boundary; the conventional estimation of exposure is based only on the *short-range interaction paradigm* and is not sufficient to find the level of exposure caused by distributed emissions. Conventional analysis is valid as long as there is *only one* mobile phone and also the boundary is *not reflective*. These conditions are not appropriate for considering current situations. Thus, we will derive a simple and generic formula for electromagnetic field and demonstrate the possibility of high levels of exposure in certain situations. Although we initiated this analysis as a result of being motivated by an incident in a public train, the following formula is applicable to more general situations. The physical quantity that we will estimate is the average equivalent poynting vector P (W/m^2) which represents the energy flux, and it is used to describe the level of exposure. We work within the framework of classical electromagnetism.[5)] Comparison of the result is made with international guidelines for exposure limits, for which extensive studies on possible problems have been performed.[6)]

Consider a closed box (system) with a reflective surface boundary, in which sources of electromagnetic waves are spatially distributed. Some parts of the boundary may be nonreflective or open. We assume for simplicity that waves coming from different sources are incoherent. Conservation of energy in the electromagnetic field leads directly to the balance equation for the electromagnetic energy, U, accumulated in the system,

$$\frac{\mathrm{d}}{\mathrm{d}t}U + J_E = W_r, \tag{1}$$

where J_E and W_r are an outward energy flux at the boundary and the sum of emission powers in the system, respectively. Our concern is only the average energy density that corresponds to the equivalent poynting vector, because the deviation from the average value should be small in the case of a high reflection probability at the boundary. Thus, according to the conventional method of statistical physics, we hereafter ignore the details of the geometry of the system and introduce the characteristic length of the system L^* that

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is a mean free path between successive reflections at the boundary, where the electromagnetic wave is assumed to behave as a *ray* which propagates freely. The characteristic time, t^*, is also defined through L^* and the velocity of the light, c, as $t^* = L^*/c$, that is, the mean free time between reflections. If there were no reflection at the boundary, all of the energy in the system would diffuse through the boundary in time t^*. Hence, we have the relation,

$$t^* \cdot J_E = U. \tag{2}$$

The effect of reflection is incorporated in the right-hand side of eq. (1) as an additional emission term. The power introduced into the system by the reflection is a product of the flux J_E and the *average* reflection probability,[7] R. With eqs. (1) and (2), we reach the balance equation including the effect of reflection:

$$\frac{\mathrm{d}}{\mathrm{d}t}U + \frac{cU}{L^*} = W_r + \frac{cU}{L^*}R. \tag{3}$$

As a stationary solution, which is realized for a timescale longer than t^*/k_d, we have

$$U = \frac{L^* W_r}{ck_d}, \tag{4}$$

where k_d is the average dissipation probability at the boundary defined as $k_d \equiv 1 - R$; its value lies between 0 and 1. Summing up the possible multiple reflection terms gives the same stationary result. The average equivalent poynting vector, $\langle P \rangle$, is therefore obtained through the relation $\langle P \rangle = uc = \frac{U}{V}c$, where u is the energy density and V is the volume of the system, as

$$\langle P \rangle = \frac{L^* W_r}{V k_d}. \tag{5}$$

This is the main result of the study. This simple formula predicts the average strength of the electromagnetic field in the system. We note that the analytical expression of eq. (5) itself was derived in a generic situation. The reader may apply it to several specific systems; for example, buses, elevators, prefabricated houses, concert halls and so on. The differences between the situations may be accounted for by changes in the parameters. We also note that the formula may be directly derived by dimensional analysis for the system characterized by four parameters: the mean free path L^*, the total emission power W_r, the system volume V, and the average dissipation probability k_d. If we introduce the average emission power per mobile, w_r, the total emission power, W_r, is written as $W_r = Nw_r$, where N is the number of sources (mobiles).

From this result, we learn that the exposure level rapidly rises as the dissipation probability, k_d, decreases to zero, which would be the case if all boundaries were made of a metal with a reflection probability near unity; an example may be an elevator without windows. This mechanism of small dissipation in metal is already utilized in waveguides for transporting microwave with minimum loss. On the contrary, the conventional estimation corresponds to the case that $k_d = 1$ in eq. (5), where the exposure level is minimum. The level of exposure $\langle P \rangle$ increases in proportion to the total emitted power W_r, which in turn increases in proportion to the number of mobiles N; this *mass* (additive) *effect* has scarcely been discussed in the literature.[2]

Although the formula is applicable to various situations, an order estimation for a specific example is useful for demonstrating how to apply the formula to a concrete system, and this result is *never* negligible in certain situations. We emphasize that our aim is not to find an individual value of exposure in a specialized situation, but to point out the significance of the phenomenon. Readers may perform individual calculations using the formula [eq. (5)] with a special set of parameters. In order to perform the order estimation, we require the characteristic values, L^*, W_r, V and k_d. Here we confine ourselves to the typical values for a commuter train car in Japan. We use the values for a car in a series 3000 train of Tokyu Corporation, one of the most recently introduced commuter trains in metropolitan areas of Japan, for which $V = 112\,(\mathrm{m}^3)$, and $L^* \sim \sqrt[3]{V} = \sqrt[3]{112}\,(\mathrm{m})$.[8] Since the bodies of modern trains are made of metals, the reflection probability inside the body may be approximated as unity because the dissipation at the point of reflection is negligible compared to other types of dissipation, for example, through windows.[9] Because waves are assumed to disappear irreversibly through the window, the dissipation probability, k_d, may be estimated in the first approximation from the ratio of the area of the windows to the gross surface area of the car. In our case (Tokyu series 3000) it is estimated as $k_d = 0.10$.[11] The total emission power also depends significantly on the situation. For greater generality, we demonstrate exposure levels at three different values, $W_r = 5, 20, 100$ watts, with the reference level for general public exposure of 1 GHz given by the International Commission on Non-Ionizing Radiation Protection (ICNIRP).[6] The exposure level increases as the dissipation probability decreases. If we decrease the power, W_r, the critical value of the dissipation probability decreases. In the case of a large power, $W_r = 100$, the average exposure level is of the order of the reference level solely because of the mass (additive) effect of the waves (even without the effect of reflection). Since we have not yet introduced any special parameters except for the volume of the system, one can use this graph (Fig. 1) to predict exposure levels of other systems (not only trains) of similar volume.

To clarify how the emission power, W_r, corresponds to the situation on the train, we illustrate it with a specific example. In a commuter train, passenger capacities are as follows: designed passenger capacity (100% *jyosharitsu*) is 151 persons, and the seating capacity is 54 or 51 persons.[11] Since the proportion of existing passengers to the designed passenger capacity (*jyosharitsu*) can exceed 200% under the most crowded condition, a car can hold more than 300 persons. Thus, the case $W_r = 100$ watts corresponds, for example, to the situation in which each of 300 mobiles emits a power of 0.33 watts; the case $W_r = 20$ watts corresponds to the situation in which 50 mobiles emit a power of 0.4 watts each, and so on. As the average dissipation probability in the Tokyu series 3000 is $k_d = 0.10$, the critical total power according to the ICNIRP reference level is $W_r = 12$ watts. Note that a mobile communicator emits power to some degree as long as it is switched on.[12] For more detailed consideration, here we note two uncertainty factors: i) the presence of passengers which is assumed to increase the average dissipation probability; ii) the shielding effect of

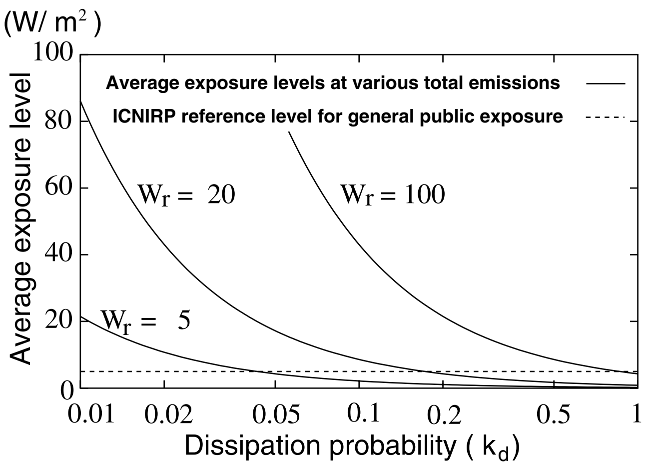

Fig. 1. Average exposure level $\langle P\rangle$ is shown as a function of the average dissipation probability, k_d: $\langle P\rangle = \frac{L^* W_r}{V k_d}$, where L^*, V, k_d, and W_r are the characteristic length of the system, the volume, the average dissipation probability, and the total power of emissions in the system, respectively. The curves represent three different powers of total emission, $W_r = 5$, 20, and 100 watts, where $V = 112\,(\mathrm{m}^3)$, and $L^* = \sqrt[3]{V} = \sqrt[3]{112}\,(\mathrm{m})$ is assumed. The horizontal dotted line indicates the reference level for general public exposure (1 GHz) set by ICNIRP. The reader may observe that the exposure level has dependence on several parameters. By scaling, one can obtain the dependence on other parameters.

windows, of which the characteristic length is comparable to or less than the wavelength (0.3 m at 1 GHz). The former decreases the level of exposure, while the latter increases it.

On the basis of this observation, we conclude that in spite of several uncertainty factors there is the non-negligible possibility that the simultaneous use of a number of mobiles in an area with a reflective boundary creates a level of exposure which can exceed that stipulated in the ICNIRP guidelines. Let us consider a commuter train that unexpectedly stops between stations due to an incident (typical for morning trains in metropolitan areas of Japan). What will passengers with mobile phones, who find themselves to be late for work, do? Once a closed area is filled with electromagnetic waves to a considerable level, the effect of their interference on people with electromedical instruments could be serious, because they have no way to avoid the emissions.[13)]

In this paper, we have analyzed how the exposure level increases depending on the situation, by reflection and additivity of electromagnetic waves. We analytically derived a generic formula with which one can predict the possible exposure level. For an example of a realistic situation, we applied the formula to a commuter train and performed an order estimation of the possible exposure level. It was shown that the simultaneous use of a number of mobile communicators in a closed area may result in a considerable level of exposure, as high as that determined by the ICNIRP to be the limit for public safety.[6)] These results are easy to understand: Consider a dark room with a single light with low power, where all of the boundaries, walls, ceiling and floor, are black. If we cover the black boundaries with mirrors, it significantly increases the brightness without incurring any additional cost for power for lighting. Also, if we increase the number of lights, the brightness will increase throughout the room. The mechanism of the increase of intensity is completely the same for this light and the electromagnetic waves of the present case, because both are governed by the same fundamental properties of electromagnetism, namely, reflectivity and additivity. Therefore, the emergence of the intensive field is not surprising. Increasing public exposure to electromagnetic wave emission is a form of environmental pollution; in both cases, naive personal consumption will lead to global pollution, which eventually may hurt humans. Since the increase of electromagnetic field by reflective boundaries and the additivity of sources has not been recognized yet, further detailed studies on various situations and the development of appropriate regulations are required.

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1) Fuyōdenpataisakukyōgikai (Electromagnetic Compatibility Conference Japan): *Keitaidenwatanmatsutōno Shiyōnikansuru Chōsahōkokusho* (Guidelines on the Use of Radiocommunication Equipment such as Cellular Telephones —Safeguards for Electronic Medical Equipment—) (Association of Radio Industries and Businesses, Tokyo, 1997) [in Japanese].
2) LINK Collaborative Research: *Electromagnetic Compatibility Aspects of Radio-Based Mobile Telecommunications Systems* (ERA Technology Ltd, Surrey, 1999).
3) Department of Health, U.K.: *STEWART REPORT and the UK Government Response to the Report* (Department of Health, U.K., http://www.doh.gov.uk/mobile.htm, 2000).
4) WHO: *Electromagnetic Fields and Public Health* (Fact Sheet No. 193, revised version) (WHO, http://www.who.int/inf-fs/en/fact193.html, 2000).
5) For example, W. K. H. Panofsky and M. Phillips: *Classical Electricity and Magnetism* (Addison–Wesley, Cambridge, 1961).
6) International Commission on Non-Ionizing Radiation Protection: *Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Field* (ICNIRP, Oberschleissheim, 1998).
7) Average reflection probability is calculated, in the first approximation, as follows: Imagine a surface boundary at which the electromagnetic wave is reflected (or dissipates). Assume that the surface is made of a material which is fully reflective, except for windows through which the wave dissipates. Assume that the ratio of the area of the windows to the total surface is 10%. Then, the *average* reflection probability, R, is approximated as 0.9. Thus, the average dissipation probability $k_d = 1 - R = 0.1$.
8) Tokyu Corporation (private communication).
9) The reflection probability, in principle, depends strongly on the conditions. However, in the microwave frequency region, it is known that the reflection probability may be treated as almost unity in comparison with other dissipation processes: Let us consider the reflection probability of the electromagnetic wave propagating perpendicular to the surface of the reflective boundary. The reflection probability, r, can be estimated using the formula applicable to the wave with length longer than that of visible light, $r = 1 - 2\sqrt{2\epsilon_0\omega/\sigma}$, where ϵ_0, ω, and σ are the dielectric constant of vacuum, the angular

frequency of an electromagnetic wave and the electric conductivity, respectively.[5)] By using an experimental value for the electric conductivity,[10)] we obtain the reflection probability. For aluminum, it is 0.9999. Since it is known that the values of electric conductivity for most metals lie in the order of approximately 10^7 ($\Omega^{-1}\mathrm{m}^{-1}$), the reflection probability is estimated as approximately 0.9998. This shows that the dissipation of the wave upon reflection is negligible compared to other dissipation processes in the present case.

10) *Rika Nenpyo* (Chronological Scientific Tables), ed. National Astronomical Observatory (Maruzen Tokyo, 1999) [in Japanese].

11) In a conventional car designed only for passengers, which has no room for a driver or a conductor, the sum of all window areas is 21.1 m^2, and the total surface area is 201.1 m^2. The ratio of the two values gives the average dissipation probability, $k_d = 0.10$ (courtesy of Mr. Tamaoki of Tokyu Corporation). In the case of a car of series 201 of JR-East, which is used for rapid commuter trains on the Chuo Line (Chuo-Kaisoku) in Tokyo, the value is estimated to be approximately the same, $k_d = 0.10$, where the calculation was performed according to the plan of the car presented by the East Japan Railway Company. A regulation on the use of mobile phones in trains was introduced by Tokyu Corporation in October 2000.

12) The output of a mobile communicator may depend on the intensity of the wave from a base station. As shown by the ratio of the window area to the total body surface of the car which corresponds to the average dissipation probability, the cabin of a train is largely shielded electromagnetically. Thus, the wave from the base station is considerably weakened inside the car. It is known that the weaker the intensity of the wave that reaches the mobile phone from the base station, the more power the mobile phone emits. We also note that the maximum output power of a mobile phone is 0.6 watts for analog phones, and 0.8 watts for digital phones (burst value) in Japan.[1)] In the report by W.H.O., the maximum output power is stated to range from 0.2 watts to 0.6 watts.[4)]

13) Experiments on animals with cardiac disease who are helped by a pacemaker will directly prove the risk of a intensive exposure. One report[1)] suggests that the interference can be fatal even *below* the reference level set in the ICNIRP guidelines for the general public.