

Irregular activation of individual sweat glands in human sole observed by a videomicroscopy

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Abstract

Sweat secretion from individual sweat glands on the human sole was observed in four male subjects by using a videomicroscope and correlated with sudomotor neural activity recorded from the tibial nerve by means of microneurography. Individual sweat glands could be distinguished as active, less active and inactive according to the incidence of sweat secretion during spontaneous sweating. The threshold amplitude of the sudomotor burst necessary for sweat secretion varied from gland to gland. The number of sweat secretion was significantly related to the threshold amplitude. Sweat glands often failed to produce sweat secretion even when a suprathreshold burst occurred: only $46.1 \pm 3.8\%$ (mean \pm S.E.M.) of the suprathreshold bursts elicited sweat secretion. Failure of the sweat secretion tended to appear after several bursts occurred consecutively with short intervals. In spite of the variability in sweat gland activity, the number of sweat glands recruited was linearly related to the amplitude of the sudomotor burst ($P < 0.001$). Thus, although sweat secretion from each sweat gland depends primarily on the intensity of sudomotor neural activity, the activity of each sweat gland may fluctuate temporally as the result of irregular activation of sudomotor fibers and possibly some intrinsic factors of the gland. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Eccrine sweat glands are controlled by a central sudomotor mechanism via the sudomotor nerve system. Postganglionic sudomotor fibers contact sweat glands using acetylcholine as a transmitter. Postganglionic sudomotor impulses stimulate the sweat secretory process in the sweat gland and provoke expulsion of sweat on the skin surface from the pore. Postganglionic sudomotor fibers fire in burst fashion, so that sudomotor burst activity is followed by sweat response. (Hagbarth et al., 1972; Hallin and Torebjörk, 1974; Bini et al., 1980a,b; Fagius and Wallin, 1980; Sugeno et al., 1990, 1998; Okamoto et al., 1994).

When the sweating rate is recorded by a continuous method (e.g., ventilated-capsule method), the sweat response is represented by a transient bulge of the sweat rate

curve, referred as sweat expulsion (Ogawa and Sugeno, 1993), although the sweat response is otherwise represented by an electrodermal response. The amplitude of the sweat expulsion or electrodermal response is linearly related to the amplitude of the sudomotor burst (Bini et al., 1980a; Sugeno et al., 1990), and thus a strict quantitative neuro-effector relationship is obtained.

Two hundred to six hundred sweat glands are distributed in a 1-cm² area on the palm or the sole (Kuno, 1956; Szabó, 1962). Undoubtedly, a single postganglionic sudomotor neuron governs multiple sweat glands, and a single sweat gland is governed by multiple postganglionic neurons (see Discussion). However, the detailed mechanisms for controlling a single sweat gland have not been clarified.

A few studies have investigated the activity of a single sweat gland in the palm with a microscope and indicated that sweat glands are activated simultaneously in response to sudomotor nerve activity, but not all the glands are recruited when a sudomotor nerve activation occurs (Saito,

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1934, cited in Kuno (1956); Nishiyama et al., 1994). Thus, the activity of sweat glands differs from gland to gland, and the activity of a single gland may fluctuate as time elapses, although the characteristics of fluctuation were not examined.

The present study analyzed the pattern of activation of a single sweat gland to elucidate the activation mechanism of a single sweat gland. We examined quantitatively activities of a single sweat gland in the sole, where mental sweating occurs synchronously with the palm, and correlated the results with postganglionic sudomotor nerve activities that were recorded microneurographically as multi-unit bursts. The multi-unit burst activity was analyzed to estimate the threshold of each sweat gland.

2. Materials and methods

2.1. Subjects

Four healthy males who have no massive hyperkeratosis or no skin eruptions in the sole were used as the subject. Three of the subjects were trained swimmers. Their ages ranged from 19 to 30 years (23 ± 2.4 years, mean \pm S.E.M.). They were informed of the purpose and the protocol of this study and consented to the experiment. The study was approved by the Human Research Committee of the Research Institute of Environmental Medicine, Nagoya University.

2.2. Experimental protocol

Experiments were performed in a room where the ambient temperature was maintained between 26°C and 29°C. The subjects, wearing a cotton shirt and shorts, were positioned supine on an experimental bed (GH-715, OG Giken, Okayama, Japan).

Sweat secretion of individual sweat glands was observed in a small skin area (approximately 0.3×0.2 cm) on the thenar eminence of the sole by means of videomicroscopy with $100\times$ magnification. Skin sympathetic nerve activity (SSNA) was recorded from the tibial nerve at the popliteal fossa, which innervates the test skin. The sweat rate, skin potential activity and skin blood flow were measured at sites close to the area of observation. Subjects were allowed to talk but were required to avoid active body movement during the experiment. At the end of each experiment, electrical stimulation was applied to the wrist skin, usually 10 times at intervals of 10 to 35 s at a constant intensity, to induce a moderate to severe painful sensation.

2.3. Observation and identification of sweat secretion

The probe of a videomicroscope (VH-6300, Keyence, Osaka, Japan) equipped with a zoom lens was fixed over the test skin using a tripod. The test area, covering 0.06

cm², included 19 to 32 glands. Images of the videomicroscope were recorded by a Hi-8 video tape recorder (EVO-9500A, Sony, Tokyo, Japan). To facilitate the evaporation of sweat accumulating on sweat gland pores, the observation area was ventilated continuously with dry air (0.5 l/min). A strobe flash was reflected toward the observation area at the start and the end of experiment to synchronize the video images and the other simultaneously recorded parameters. After the experiment, the timing of sweat secretion from each sweat pore was determined every 1/30 s with the aid of video playback.

Previous to the experiment, test field of the sole was determined as an area where sweat gland pore-like structures were arranged at similar spaces to investigate a representative region of the sole and to avoid the misunderstanding by the sweat glands, the pore of which was obstructed by localized hyperkeratosis.

2.4. Recording of SSNA

A tungsten microelectrode with a tip diameter of 1 μ m and an impedance of 3 to 5 M Ω was inserted percutaneously into the tibial nerve fascicle at the level of the knee. The position of the electrode was adjusted precisely by hand, until SSNA was encountered. SSNA was identified as a spontaneous, irregular burst activity that is not synchronous with heartbeat (Hagbarth et al., 1972; Hallin and Torebjörk, 1974; Bini et al., 1980a; Fagius and Wallin, 1980; Sugeno et al., 1990; Okamoto et al., 1994). Such bursts are evoked reflexively by mental or sensory stimulus and are followed with a constant latency of 2–3 s by a sweat response or a transient reduction of skin blood flow (Sugeno et al., 1990; Okamoto et al., 1994). The SSNA response was monitored acoustically by a loudspeaker and visually by an oscilloscope (5113, Tektronix, Beaverton, OR, USA). SSNA signals were amplified with a preamplifier, processed by band-pass filters (500–5000 Hz) (E-3201A, NF Circuit Design, Yokohama, Japan) and stored in a digital data recorder (PC116, Sony-Magnescape, Tokyo, Japan). The processed SSNA signals were full-wave rectified and integrated with a time constant of 0.1 s.

2.5. Measurements of sweat rate, skin potential activity and skin blood flow

The local sweat rate was recorded by the ventilated-capsule method using capacitance hygrometers (HMI-23, Vaisala, Helsinki, Finland). A sweat capsule covering an area of 1.13 cm² was ventilated with dry nitrogen gas at a flow rate of 0.3 l/min, and the humidity change of the effluent air was sensed. The distance from the capsule to the sensor was 5 cm; the delay of sensing, which was estimated to be 0.09 s, was corrected. The sensitivity of the measurement system was calibrated to the evaporation rate by infusing 1 μ g distilled water into the dry nitrogen stream.

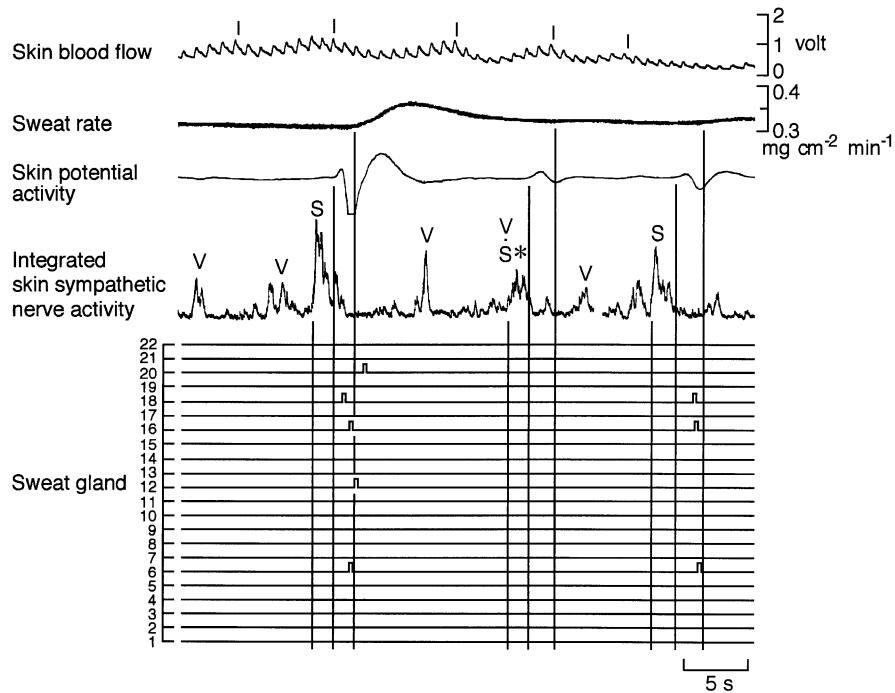


Fig. 1. Secretion of individual sweat glands and various effector responses to spontaneous sudomotor bursts during mild sweating. Skin blood flow, sweat rate, skin potential activity and skin sympathetic nerve activity recorded from the tibial nerve are indicated. The lower panel indicates the timing of sweat secretion from individual sweat glands observed on a small area of the sole by a videomicroscope. The numerals 1 to 22 along the vertical bar represent individual glands. Two sudomotor bursts (S with no asterisk) elicited sweat secretion from three or five glands (Nos. 6, 12, 16, 18, 20). Another sudomotor burst (S with asterisk) did not elicit any sweat secretion, although the burst caused small responses in skin potential and local sweat rate. Skin vasoconstrictor bursts (shown as V) induced a transient reduction of skin blood flow. One of the sudomotor bursts contains the vasoconstrictor component. Three vertical lines show the onsets of sudomotor burst, skin potential response and sweat response, in this order.

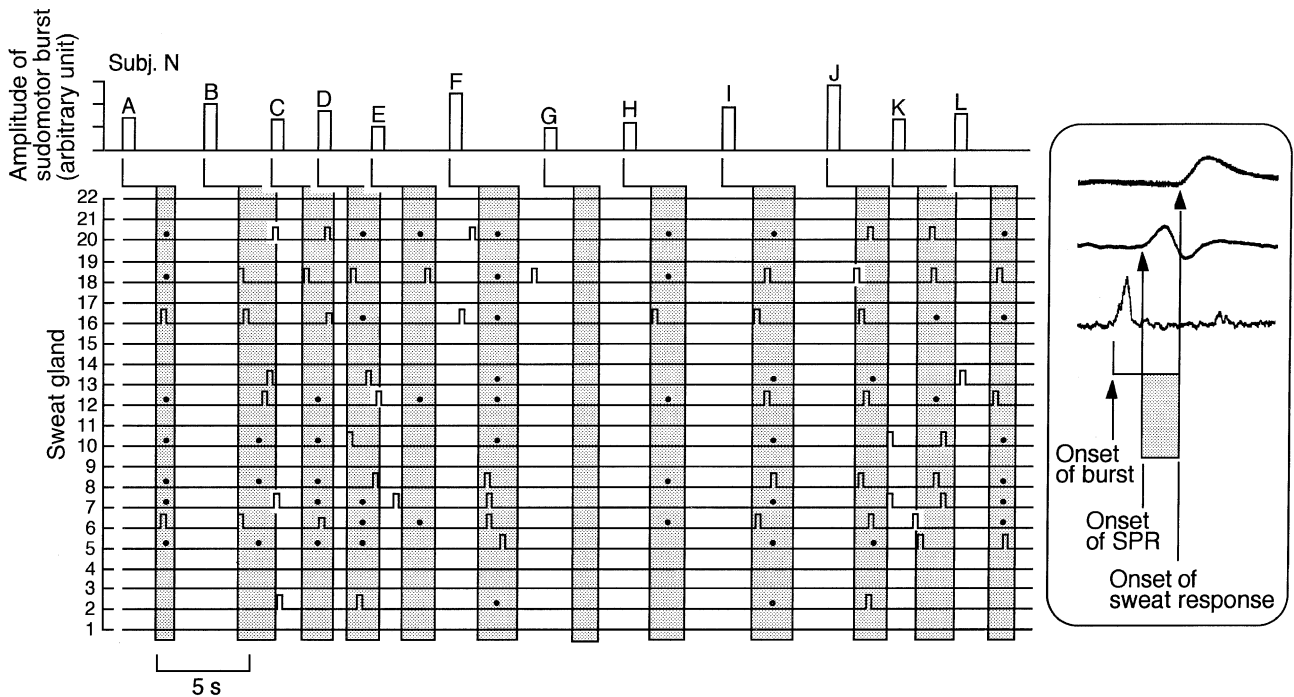


Fig. 2. Sweat secretion from individual glands during moderate spontaneous sweating. The top bars A–L show the relative amplitude of sudomotor bursts. The short vertical bars below the top bar indicate the onset of each burst. The initial lines of the dotted squares show the onset of the skin potential response (SPR), and the terminal lines show the onset of the sweat response, as shown in the inset. Dots denote the failure of response following a suprathreshold burst (see text for the definition of suprathreshold burst).

Skin potential activity was measured with surface electrodes, one attached to the sole as the recording electrode and the other to the midpoint of the dorsal foot as the reference electrode. The skin potential was amplified with a bioelectric amplifier (AB-621G, Nihon Kohden, Tokyo, Japan) at a time constant of 2 s and was displayed on a pen recorder (Recti-Horiz, NEC-San-ei, Tokyo, Japan).

Skin blood flow was measured by means of laser Doppler flowmetry (ALF21, Advance, Tokyo, Japan) with a probe attached to the test site, and was displayed on a pen recorder.

2.6. Definition of SSNA burst

SSNA bursts greater in amplitude than 10% of the maximum among the spontaneous sudomotor bursts were selected. Sudomotor bursts were then defined as bursts that were followed by a skin potential response (SPR) and/or sweat expulsion with constant latencies of approximately 2.5 s (Hagbarth et al., 1972; Hallin and Torebjörk, 1974; Sugeno et al., 1990, 1998; Okamoto et al., 1994). Sudomotor bursts were further classified into pure sudomotor bursts, which are followed only by a sweat response, and mixed bursts (composed of sudomotor and vasoconstrictor impulses), which are followed by both a sweat response and a skin blood flow reduction.

By definition, a total of 146 SSNA bursts were identified as sudomotor bursts during spontaneous sweating in all subjects (25 to 50 bursts in each). Nine out of one hundred forty six sudomotor bursts did not produce any sweat secretion within the observation area (as exemplified by asterisks in Fig. 1). The absence of visible secretion might be attributed to the scarcity of the observed sweat glands in this study. Eighteen out of one hundred forty six bursts could not be analyzed because sweat secretions were not separated due to extremely short intervals after the preceding burst. Five out of one hundred forty six bursts could not be analyzed due to recording errors of effector responses or video image. The remaining 114 sudomotor bursts were analyzable. Out of these 114 sudomotor bursts, 82 (71.9%) were pure sudomotor bursts and 32 (28.1%) were mixed bursts. Unless otherwise specified, 114 sudomotor bursts, including pure sudomotor and mixed bursts, were subjected to analysis in this study. In addition, 40 sudomotor bursts that were evoked by painful electric stimulation were analyzed for comparison.

2.7. Statistical analysis

The relationship between the two variates was analyzed by linear regression analysis. The difference between the linear regression lines was tested using analysis of covari-

ance. The significance level was taken as a *P* value of 0.05. Data were expressed as mean \pm S.E.M.

3. Results

Ninety-four sweat glands were observed by videomicroscope in four subjects. Sweat secretion was observed for 9.5 to 15 min for each subject, during which no mental stimuli were given. Forty-three out of ninety-four sweat glands (45.7%) produced sweat secretion during the observation period, whereas the remaining 51 glands produced no detectable sweat. The mean sudomotor burst incidence throughout the observation period was 1.93 to 4.17 (2.99 \pm 0.47) burst/min.

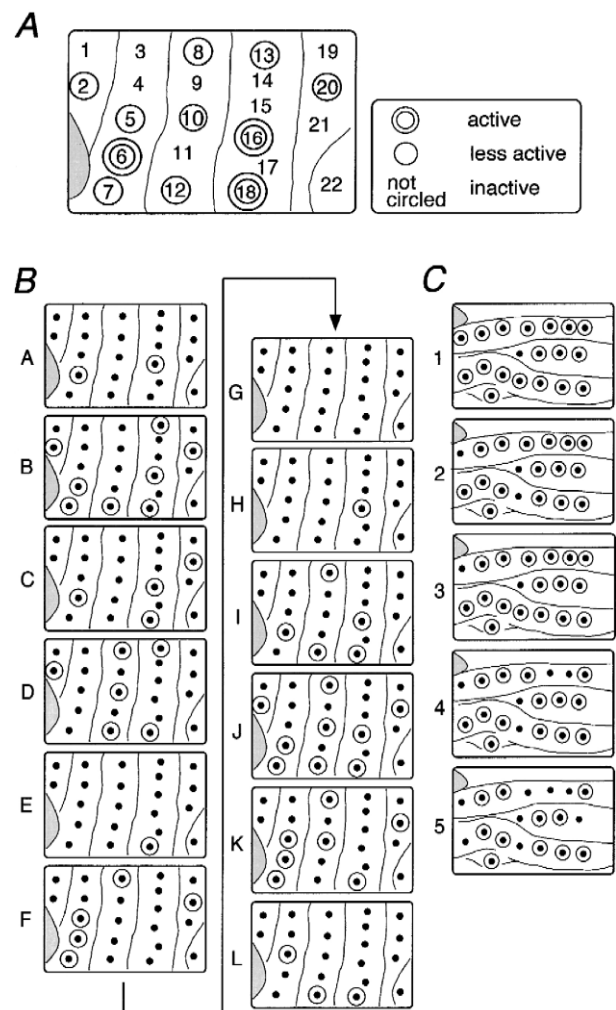


Fig. 3. Geographical distribution of individual sweat glands. (A) Distribution of individual sweat glands on the sole according to their activity level in an experiment for which the secretion data is represented in Fig. 2. (B) Sequential pattern of activation of individual glands for each spontaneous sudomotor burst (A to L). Data are shown for the case of Fig. 2. Dots indicate the location of each gland, and encircled glands indicate activated glands. (C) Sequential pattern of activation of individual glands for five sudomotor bursts evoked by painful electric stimulation. From the data shown in Fig. 4.

3.1. General pattern of sweat secretion from individual glands

Fig. 1 shows a representative record of mild sweating, where sudomotor bursts occurred sparsely, whereas Fig. 2 shows a record during moderate sweating, where sudomotor bursts occurred more frequently. Sudomotor bursts were followed by SPR at a latency of 1.33 ± 0.33 s, by sweat secretion at a latency of 2.29 ± 0.03 s, and by sweat expulsion at a latency of 3.22 ± 0.03 s. Although sweat secretions were not exactly simultaneous among the glands, most instances (343 out of 358, 95.8%) occurred within the period from the onset of SPR to that of sweat expulsion.

Generally, sweat glands could be divided into three groups according to the frequency of sweat secretion: active, less active and inactive glands. In the example of Fig. 2, 14% were active, 36% less active, and 50% inactive (under the definition of an active sweat gland as one that responded to more than 50% of the sudomotor burst that occurred), although this proportion greatly varied with the subject and with the intensity of sweating.

Active sweat glands, for instance, Nos. 6, 16 and 18 in Fig. 2, nearly always responded when the preceding interval was long enough (bursts B, I and J), but often failed to

respond especially after several bursts occurred consecutively with short interval (bursts D, E, L for No. 6; bursts D, F, K, L for No. 16; burst F for No. 18). It should be noted that, when active glands failed to respond, less active glands seemed to compensate. For instance, failure of response in sweat glands 6 and 16 to burst D appears to be compensated by the responses of sweat glands 2, 8, 10, 12 and 13 in Fig. 2.

As shown in Fig. 3A, active sweat glands appeared to be distributed sporadically over the observation area, with no tendency to be localized. Less active glands also appeared to be distributed evenly all over the observation area. The geographical pattern of sweat gland recruitment greatly varied from burst to burst (Fig. 3B), so that no consistent pattern of sweat gland recruitment was detected. Even when the same number of sweat glands was recruited, identical patterns of sweat gland recruitment were not obtained.

Severe pain applied to the skin may produce submaximal sudomotor bursts on the sole. Sudomotor bursts evoked by painful electric stimuli were usually larger in amplitude than those occurring spontaneously: the mean amplitude of pain-evoked bursts was $140 \pm 11.3\%$ of the largest among the spontaneous sudomotor bursts (Fig. 4). The majority of sweat glands responded to such submaximal bursts without

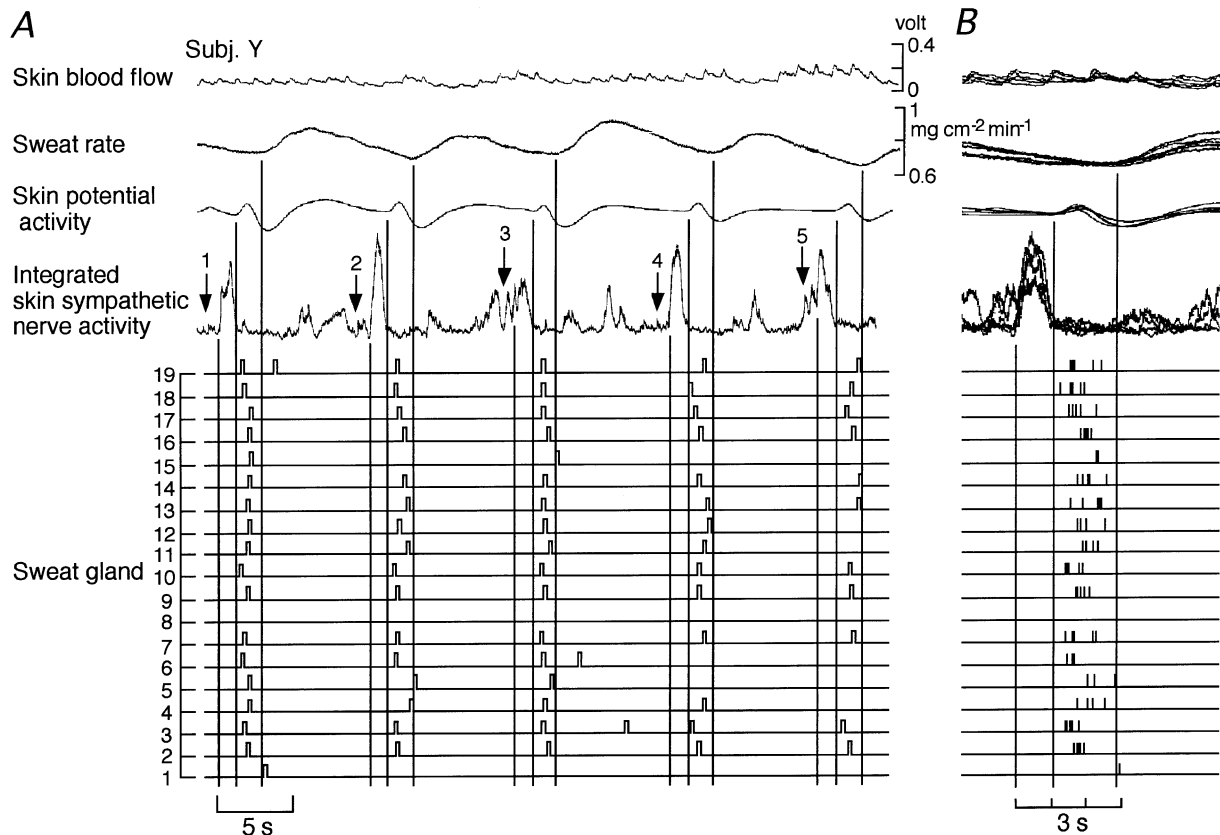


Fig. 4. (A) Continuous recording of the responses to five painful electric stimuli (\downarrow) applied to the wrist at intervals of 10 s. (B) Superimposed tracing of the five consecutive responses.

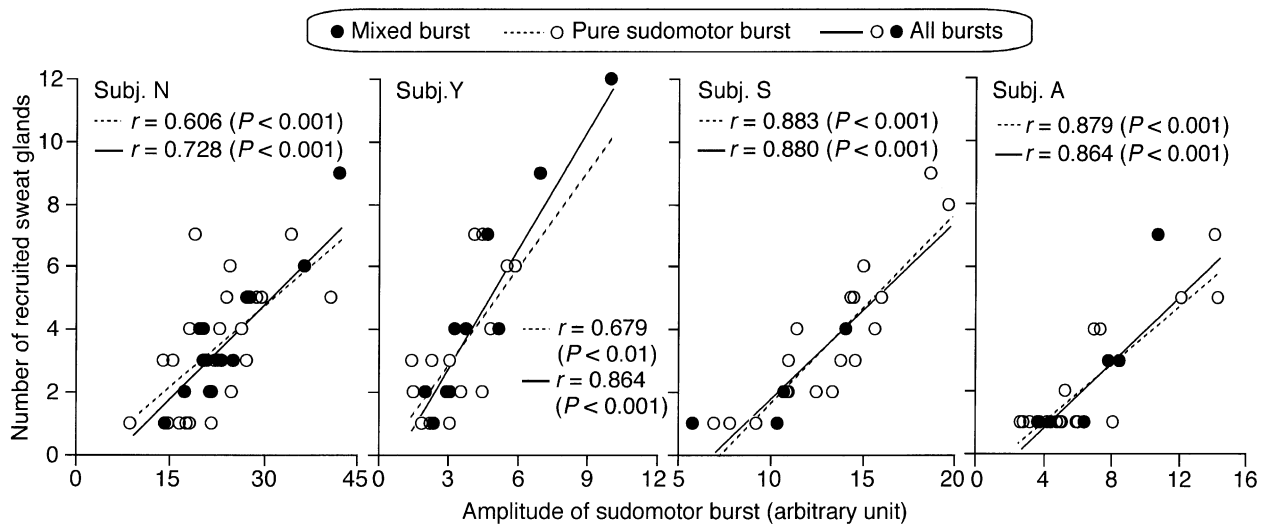


Fig. 5. Relationship between amplitude of sudomotor burst and the number of recruited sweat glands. The closed circles indicate mixed bursts that contain sudomotor and skin vasoconstrictor components. The open circles indicate pure sudomotor bursts. The dotted lines depict the regression lines for pure sudomotor bursts, and the solid lines indicate all the bursts including pure sudomotor and mixed bursts. The number of recruited sweat glands is linearly related to either the amplitude of the pure sudomotor bursts or the amplitude of all bursts.

fail. In the example of Fig. 4, 11 of 19 (58%) glands responded to all of the pain-evoked sudomotor bursts, and in particular 18 of 19 (95%) sweat glands produced sweat secretion once or more. For the evoked bursts, the geographic pattern of recruited sweat glands did not change greatly burst by burst (Fig. 3C).

With the pain-evoked bursts, it was also observed that the latency from the onset of sudomotor burst to sweat

secretion varied less in some sweat glands, whereas it varied rather greatly in other sweat glands, although the range of variation did not exceed the duration of the sudomotor burst (Fig. 4B). The mean latency was 0.59 ± 0.06 s within a sweat gland.

In Fig. 5 the number of sweat glands recruited with a single burst is plotted against the burst amplitude for pure sudomotor bursts and for mixed bursts. The relationship

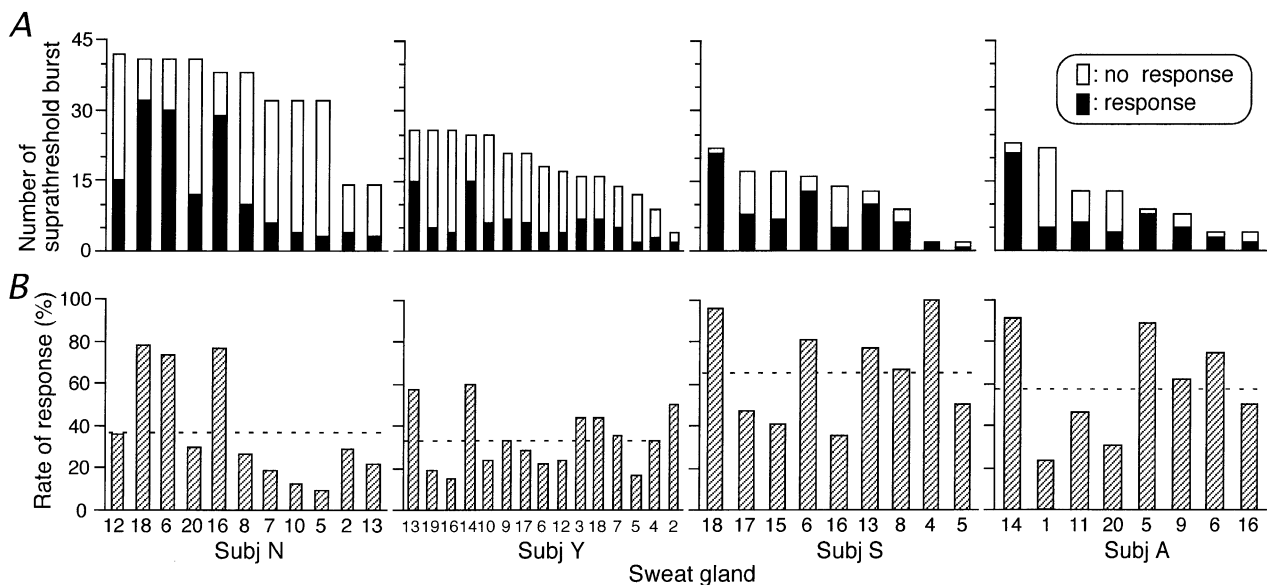


Fig. 6. Response of individual sweat glands to suprathreshold sudomotor burst. (A) The total number of suprathreshold bursts that appeared during the observation period of 9.5 to 15 min. The shaded bars indicate the number of bursts to which the sweat glands responded, and the open bars indicate those to which sweat glands did not respond. Individual glands are arranged in descending order of the threshold for each subject. (B) The ratio of the number of responses to the total number of suprathreshold bursts that occurred. Broken lines show average values for each subject: 37.2 ± 7.8 , 33.8 ± 3.7 , 66.0 ± 7.9 and 58.4 ± 9.0 (means \pm S.E.M.).

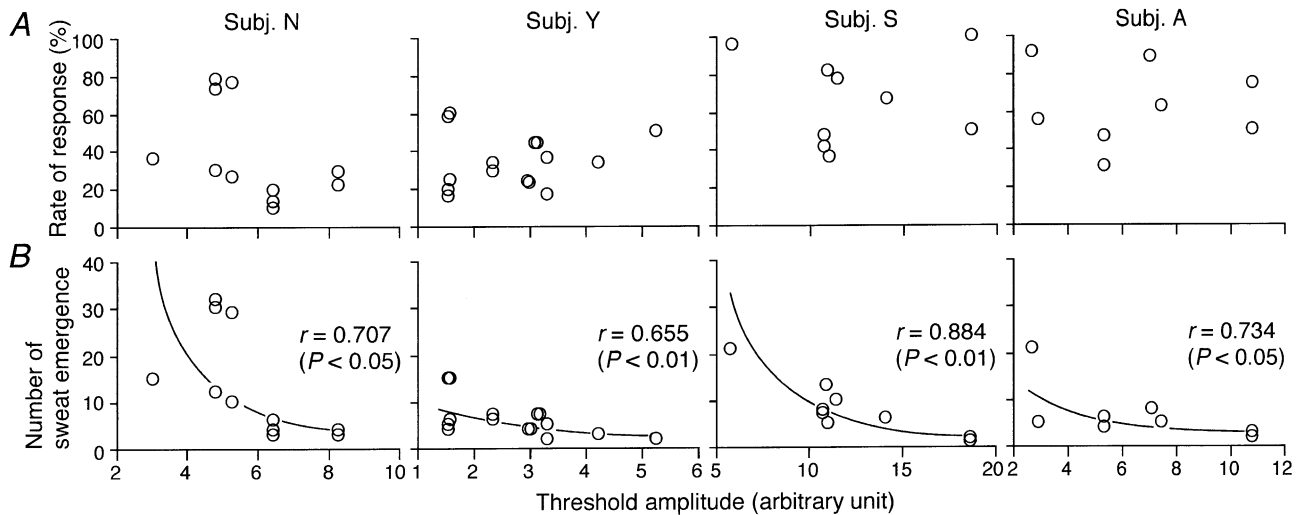


Fig. 7. Relationship between responsiveness and threshold of individual sweat glands. (A) The rate of response to the suprathreshold bursts (cf. Fig. 6B) and (B) the total number of sweat secretion are plotted against the threshold amplitude estimated by sudomotor bursts. Plots are fitted with an involutorial function. The total number of sweat secretion (B) is significantly related exponentially to threshold amplitude of the sudomotor burst in each subject.

was linear both for the pooled data of pure sudomotor bursts and mixed bursts (solid lines) and for the data of pure sudomotor bursts (dotted lines), and the former regression line was not significantly different from that of the latter. This finding illustrates that the total number of recruited glands represents the intensity of sudomotor nerve activity in any subject. Additionally, it could be said that the amplitude of mixed bursts in the present data is not influenced greatly by the vasoconstrictor component so that it reflects appropriately the intensity of the sudomotor component (this is the main reason we included the mixed bursts in the present analysis).

3.2. Threshold of each sweat gland

For further analysis we tentatively determined the threshold of a sweat gland for elicitation of sweat secretion, for each of the sweat glands that elicited sweat secretion twice or more during the observation period. The threshold was defined as the amplitude of the smallest burst that elicited sweat secretion. Fig. 6A depicts how frequently suprathreshold bursts occurred for each gland and how frequently a sweat gland responded to those suprathreshold bursts. These figures show that when suprathreshold bursts occurred, not all the sweat glands responded. Fig. 6B also shows the response ratio expressed as the number of suprathreshold burst responses divided by the number of suprathreshold bursts occurring for each sweat gland. The ratio was low with a mean value of $46.1 \pm 3.8\%$ for 43 sweat glands in four subjects. In Fig. 7A this ratio is plotted against the threshold amplitude. No significant relationship was found. In Fig. 7B the number of sweat secretion is also plotted against the threshold amplitude. The number of sweat secretion was inversely related to threshold amplitude ($r = 0.655$ – 0.884 ; $P <$

0.05), indicating that the lower the threshold of a sweat gland, the greater its activity.

4. Discussion

4.1. Variability of activity of each sweat gland

The important observation of this study is that the activity of each sweat gland varied greatly. The classical study (Saito, 1934, cited in Kuno (1956)), which observed the activity of individual sweat glands on the human palm by a skin microscope, described various types of sweat glands: always active, always inactive and those whose activity varied. Such a grouping of sweat glands was confirmed in the present study.

In spontaneous moderate sweating of the sole, active glands responded to 50–67% of the spontaneously occurring sudomotor bursts whereas less active glands responded to only 17–42% (Fig. 2). On the other hand, when submaximal bursts occurred, nearly all the glands responded. These observations suggest that the difference between active and less active glands is quantitative, and is based on a difference in threshold. In the moderate sweating, inactive glands represented a greater number of the glands. However, a great majority of sweat glands responded to almost all the sudomotor bursts that were elicited by pain stimulation (Fig. 4), suggesting that sweat glands that do not function must be very few in the sole.

It is likely that sweat gland activity fluctuates within a certain time span from active to inactive or vice versa. Our previous study reported that mean activity of some sweat glands changed greatly over periods of 30–40 min (Nishiyama et al., 1994). However, the period of such fluctuation has not been examined. It is also uncertain whether a single sweat gland possesses a proper activity

level when averaged over a long time span, and, if so, what factors determine the proper activity level (e.g., the size of the secretory coil of a sweat gland etc.).

Although the observed skin area was too small to analyze the geographical distribution of a certain population of sweat glands, it is unlikely that consistent patterns are present for the distribution of either active or less active glands (Fig. 3A). Similarly, the distribution pattern of recruited sweat glands varied from burst to burst, and even if the same number of sweat glands was recruited, the same pattern of sweat gland recruitment was never reproduced (Fig. 3B).

Despite the irregular activation of individual sweat glands, the total number of glands recruited with a sudomotor burst was proportional to the amplitude of the sudomotor burst (Fig. 5). This relationship would secure the neuro-effector function, and thus provide a basis for proportional control of sweat glands by sudomotor neural activity. This proportional relationship appears to be realized, at least in moderate sweating, by cooperation of active glands and less active glands in such a fashion that the failure of sweat secretion of an active gland is compensated by the secretion of less active glands.

4.2. *Innervation of sudomotor axons to sweat gland*

A microneurographic study (Schmelz et al., 1998) directly indicated that the mean innervation area of a single sympathetic C fiber destined for sweat glands or for skin blood vessels was 1.28 cm^2 (range of $0.24\text{--}3.5 \text{ cm}^2$) in the lower leg, dorsal foot and toes of humans. Since sweat gland density is 150 ± 15 per cm^2 in the lower leg and 250 ± 5 per cm^2 in the dorsal foot (Szabó, 1962), a single sudomotor fiber may supply an average of 192 to 320 sweat glands in these regions. Conversely, the innervation of multiple sudomotor units to a single eccrine sweat gland was neurophysiologically demonstrated in the rodent paw (Kennedy et al., 1984). The multiple innervation of the thermal sweating regions in humans is also predicted (Wilkins et al., 1938; Riedl et al., 1998).

In the present study, we observed a skin area that included 19 to 32 sweat glands, which corresponds to only 10% of the number of sweat glands that a single sudomotor unit governs. This quantity of sweat glands is too small to determine whether the pattern of sweat gland recruitment is related to the distribution of a single sudomotor unit.

4.3. *Threshold of a single sweat gland*

In past studies, sweat gland activity was estimated from a large population of sweat glands within an area of localized skin (Nadel et al., 1971) or as a single sweat gland in a localized area (Sato and Sato, 1983). The present study determined the threshold for each sweat gland using the intensity of sudomotor nerve activity. In

this analysis, the threshold was estimated by the amplitude of the sudomotor burst.

The assumption that a single sweat gland has a single, fixed threshold is to some extent justified by the observation in the present study that the lower the threshold, the greater the number of sweat secretions (Fig. 7B). When a fixed threshold was assumed for each gland, however, only 46% of suprathreshold bursts elicited sweat secretion. This low value appears to suggest that the activity of each sweat gland is not determined solely by its threshold level. Some glandular mechanism that impedes sweat gland response to suprathreshold bursts should be additionally postulated. The involvement of such a mechanism is supported partly by the observation that the failure of sudomotor bursts to elicit sweat secretion tended to appear when the recovery period after the previous activation was not sufficient, for instance, when preceding burst intervals were shortened or after the bursts occurred consecutively with short intervals (Fig. 2).

The sweat secretory mechanism is readily modified by the microenvironment around a sweat gland. First, in sweat glands isolated from the monkey palm, sweat secretion rapidly declined when glucose, a main energy source for secretion, was removed from the incubation medium (Sato, 1977). Secondly, local ischemia reduces the activity of sweat glands by modifying the sensitivity of secretory cells (Collins et al., 1959). Thus, insufficient supply of the materials essential for sweat secretion, i.e., energy source or oxygen, may lead to a transient failure of sweat response in each gland. The blood supply to each gland may be a key factor for maintaining the microenvironment around the gland.

4.4. *Neuronal mechanism of activation of each sweat gland*

On the neurophysiological basis, it is assumed that a single sweat gland is driven by the spatial summation of multiple synaptic inputs. This mechanism is described schematically in Fig. 8. In this model we presumed that neural activities are recorded from five sudomotor neurons 1 to 5 located around the tip of microelectrode (A), and as shown in B, each neuron is activated irregularly in the order represented by dots. Since the number of activated axons determines the amplitude of sudomotor bursts, the bursts a to c, activated by three axons, have identical smaller amplitudes, and burst d, activated by five axons, has a taller one. Provided that sweat gland A is innervated by axons 1 and 2 and the concomitant activation of the two axons successfully produces sweat secretion, it would appear that sweat gland A responds only to bursts b and d. Consequently, sweat gland A does not respond to bursts a and c although bursts a, b and c have the same amplitude.

Evidence on the structure and function of the sudomotor system essential for this model has been to a small extent furnished. First, it was observed that a single sweat gland

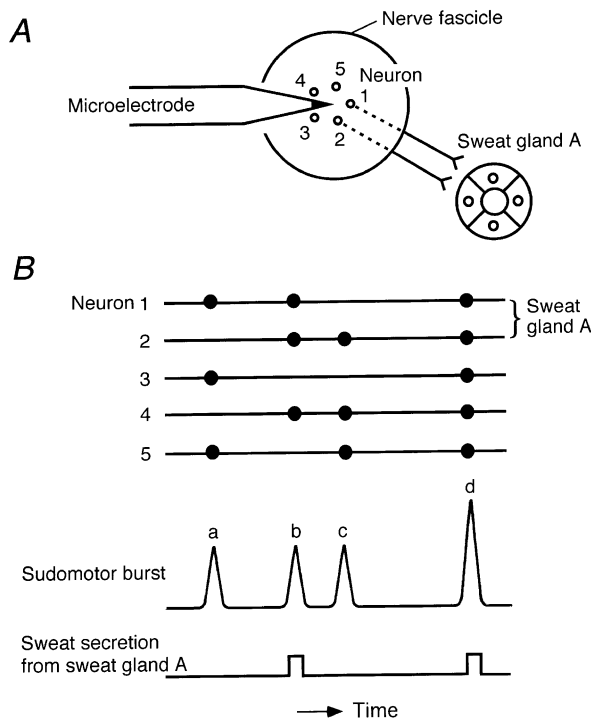


Fig. 8. Schema of a neurophysiological model for sweat gland activation. (A) A schema representing the spatial relationship between a microelectrode tip and the neurons to be recorded. (B) The idealized relationship among sudomotor burst activity, neuronal activity and sweat gland activation. This figure assumes that sudomotor bursts a, b and c, which have the same amplitude, are elicited by a spatial summation of impulses from three different neurons, and the burst d by that of all five neurons 1 to 5. The timing of excitation on neurons 1 to 5 (●) is correlated with the occurrence of sudomotor bursts and of sweat secretion from a sweat gland. Assuming that sweat gland A is activated by a spatial summation of impulses from neurons 1 and 2, then the sudomotor bursts b and d elicit sweat secretion.

is innervated by multiple sudomotor axons, as described above (Kennedy et al., 1984). Secondly, irregular activation of a single postganglionic neuron, as is postulated in Fig. 8B, has lately been demonstrated in single-unit recordings of muscle vasoconstrictor units. Macefield et al. (1994) and Macefield and Wallin (1996, 1999) reported that muscle vasoconstrictor units, which have firing properties similar to sudomotor units, do not necessarily fire at every multi-unit burst in humans at rest.

4.5. Significance of variability of sweat gland activity

It is likely that the property of irregularity may be essential for the sudomotor control system. Sudomotor bursts occur quite irregularly (Bini et al., 1980a,b; Hagbarth et al., 1972), and as described above a single postganglionic sudomotor fiber also fires irregularly, by analogy to a single postganglionic vasoconstrictor fiber destined for muscular vessels. The irregular discharge of single postganglionic fiber may be caused by the synaptic mechanism in a sympathetic ganglion. McLachlan et al.

(1997) showed that a single postganglionic neuron is driven by two or more preganglionic neurons in the cervical ganglia of the rat. Irregular activation of sweat glands appears to favor control of sweat gland function, apart from its mechanism. Evidence that irregular stimulation increases the efficacy of the neuroglandular transfer function has been provided by Kunimoto et al. (1991, 1992). They stimulated the sudomotor fibers via a microelectrode inserted into the human median nerve, and observed that irregular stimulation of postganglionic neurons potentiated sweat production as compared with the same number of regular stimulations. In conclusion, the activity of each sweat gland fluctuates considerably with every activation. This fluctuation is possibly caused by the summation of synaptic input from multiple sudomotor units. Some intrinsic factors of sweat glands may also be involved. In spite of the irregular activation of sweat glands, the total number of sweat glands to be activated is well proportional to the intensity of sudomotor neural activity.

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