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STIMULUS–RESPONSE FUNCTIONS OF RAPIDLY ADAPTING MECHANORECEPTORS IN THE HUMAN GLABROUS SKIN AREA

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SUMMARY

1. Single unit impulses were recorded from the ulnar and median nerves of awake human subjects with tungsten electrodes inserted percutaneously in the upper arm.

2. Forty-nine rapidly adapting mechanoreceptors with receptive fields in the glabrous skin area were studied. Thirty-nine units had small receptive fields with distinct borders (RA-receptors) while ten units had large fields with indistinct borders (PC-receptors).

3. The afferent response to stimuli of varying indentation amplitude and velocity of indentation, was analysed.

4. Amplitude thresholds varied from 0·05 to 1·65 mm for the RA-receptors. For the PC-receptors amplitude thresholds ranged from less than 0·05 to 1·95 mm.

5. Velocity thresholds varied for the RA-receptors from 0·4 to 39·3 mm/sec, and for the PC-receptors from 0·5 to 19·6 mm/sec.

6. The conduction velocities of the afferents were all in the A α–β range. For the RA-receptors the conduction velocities ranged from 26 to 91 m/sec (mean = $55·3 \pm 3·4$), and for PC-receptors the range was from 34 to 61 m/sec (mean = $46·9 \pm 3·6$).

7. The nerve impulse frequency as a function of indentation velocity was analysed for nineteen RA-receptors and four PC-receptors. A hyperbolic log tangent function of the type first introduced by Naka & Rushton (1966) in studies on S-potentials in the fish retina was found to be the best description of the stimulus–response function for sixteen RA-receptors and two PC-receptors. For the remaining units a pure logarithmic function was the best description. However, the logarithmic function may be, as found in the present study, a special case of the more general log tanh function.

INTRODUCTION

The percutaneous micro-electrode technique developed by Vallbo & Hagbarth (1968) for recording from human nerves has recently been employed to explore the population of mechanoreceptors with large diameter nerve fibres in the human glabrous skin area of the hand (Knibestöl & Vallbo, 1970). At least four distinct classes of receptors have been distinguished, two types of slowly adapting receptors and two types of rapidly adapting ones, which all have striking similarities with four well defined types in the cat and in subhuman primates (Iggo, 1963; Lindblom, 1965; Lindblom & Lund, 1966; Brown & Iggo, 1967; Chambers & Iggo, 1967; Iggo & Muir, 1969; Burgess, Petit & Warren, 1968; Talbot, Darian-Smith, Kornhuber & Mountcastle, 1968).

In order ultimately to be able to correlate different aspects of the sensory capacities of the human glabrous skin area with the properties of first-order afferents of this area, it seemed necessary to obtain additional quantitative data concerning these classes of cutaneous mechanoreceptors. The present paper is an extension of the previous study with the purpose of giving a quantitative description of the physiological properties of the two types of rapidly adapting receptors in the glabrous skin area. Mathematical descriptions of the stimulus–response relationship are given, showing that a hyperbolic tangent log function best fits the data for most of the receptors. This function was introduced by Naka & Rushton (1966) to describe the S-potentials in the fish retina, and has later been shown to be a general transfer function in several sensory systems (Lipetz, 1969, 1971), but so far it has not been considered in studies of cutaneous mechanoreceptors.

METHODS

Forty-nine single units recorded from the median and ulnar nerves were studied. These units were collected in fifteen experiments on fourteen healthy adults, seven females and seven males, age between 20 and 30 years. The nerve recording electrodes and the recording technique have been described in detail in earlier reports (Vallbo & Hagbarth, 1968; Knibestöl & Vallbo, 1970). The subject lay face downward on a couch with the upper arm extended laterally, while the forearm was directed towards the foot end of the couch. The hand and the forearm were pronated and rested on a shelf rigidly fixed to the couch. Additional immobilization was achieved by partially embedding the forearm and the hand in a block of modelling clay, leaving the volar aspects of the hand, which was directed upwards, free and accessible to mechanical stimulation. The tungsten needle electrode for nerve impulse recording was inserted in the median or the ulnar nerves approximately 10 cm proximal to the elbow.

An electromechanical stimulating system was constructed in order to deliver mechanical stimuli to the skin with precisely controlled amplitude, velocity and duration. The main components of the system and the general experimental arrangements are outlined in the block diagram in Fig. 1. The wave form generator provided

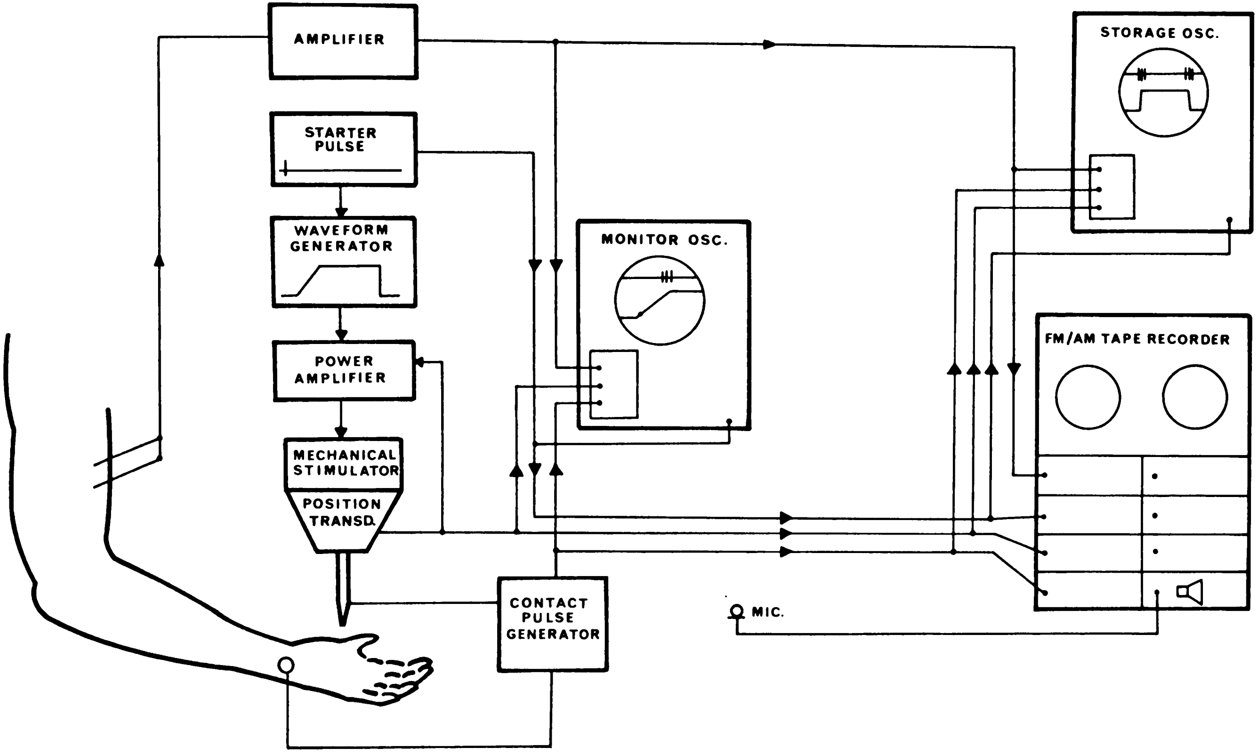

Fig. 1. Block diagram of the general experimental arrangements and the electromechanical stimulating system. A starter pulse triggered the wave form generator, which via a power amplifier controlled the mechanical stimulator. This was a moving coil electro-mechanical transducer to which the stimulating probe was attached. A differential transformer provided an analogue signal of the probe displacement. The contact pulse generator gave a short pulse when the probe touched the skin. A monitor oscilloscope displayed the rising phase of the stimulus with the contact pulse, and a storage oscilloscope was used to check the signals which were taped on the FM/AM tape recorder. A voice protocol, the nerve impulses, the stimulating probe movements, the starter pulse and the contact pulse were taped.

rectangular pulses or pulses with linearly rising and falling slopes. The final voltages, the durations and the rise and fall times were independently variable. These pulses were fed into a power amplifier driving the moving coil stimulator to which the stimulation probe was attached. The probe had a flat tip with an area of 1 mm^2. An analogue signal of the probe displacement was recorded, and the same signal provided negative feed-back to the power amplifier, improving the performance of the moving coil stimulator. The amplitude of the probe displacement was adjustable in 0·1 mm steps up to 2 mm. For identical settings, the probe displacement was constant within 10 μm in the steady state. Skin indentation velocities from 0·1 to 72 mm/sec could be produced. The stimulation device was mounted on a heavy mechanical manipulator rigidly fixed on the supporting shelf, allowing vertical positioning of the probe above any desired area of the palm and fingers.

The effective skin indentation amplitude was checked continuously with a circuit indicating the moment when the probe made contact with the skin. A battery provided a steady potential between the probe and a large remote electrode in contact with the skin, and the circuit responded with a pulse of 0·1 msec duration when the current through the probe exceeded 10^{-12} A. The contact pulse was employed to increase the intensity of the beam of the monitor oscilloscope which displayed the rising phase of the stimulus signal. Guided by the contact pulse the probe tip was set as close as possible to the skin surface.

When stimuli were delivered with a repetition frequency of 1–2/sec, it was observed that the skin contact did not occur at a constant level of the deviation signal, but rather moved up and down in a fairly regular manner. It soon became obvious that these variations occurred synchronously with the respiration, and it could be demonstrated that they were probably accounted for by movements of the skin surface: short-lasting stimuli were delivered with a frequency of about 2/sec while the respiratory movements were recorded using a mercury-filled rubber tube around the chest. Representative findings are illustrated in Fig 2*B*. The upper trace shows an analogue signal of the respiratory movements and the lower trace the variation of the skin contact level from one stimulus to another. In the latter trace the intensity of the oscilloscope beam was cut down so that only the enlightened points indicating the moment of skin contact were visible. It is clear that there was a variation in the position of the contact pulse, closely related to the respiratory cycle, the range of variation being approximately 30 μm in this case. The factor accounting for this movement of the skin surface is probably variation in the blood volume of the hand as the intrathoracic pressure varies during the respiratory cycle. However, the variation of the effective stimulus amplitude introduced by this factor did not usually exceed 20–30 μm.

Receptive fields were mapped manually with a small glass probe, using near-threshold short taps or gentle strokings across the dermal ridges. The field borders were marked on the skin, and they were later reproduced on transparent paper, from which the areas were measured.

Indentation thresholds were determined routinely in the centre of the receptive field, using stimuli with a duration of 1 sec and maximal indentation rate. The variability of the effective stimulus amplitude from one test to another as described above imposed a limitation on the accuracy with which the thresholds could be determined. The following procedure was adopted to measure the thresholds: the amplitude was varied in 100 μm steps until the maximal amplitude was reached which did not elicite a nerve impulse in the majority of a series of stimuli. The next higher amplitude then usually evoked one or two impulses at each stimulus. The threshold was defined as the mid-point between these two amplitudes. The velocity threshold was defined as the minimal slope which evoked at least one nerve impulse.

In order to estimate the conduction velocities of the afferent nerve fibres, the stimulus–response latencies were assessed and the distances from the centre of the receptive field to the recording site in the nerve were measured. The latency was defined as the time between the contact pulse and the first nerve impulse when stimuli of maximal indentation velocity and amplitude were employed. This latency was corrected for the time required to reach the amplitude threshold determined for the units.

The signals recorded on tape were filmed from an oscilloscope screen with a Grass camera, each test giving a display of the type presented in Fig. 2*A*, where the upper trace is the nerve signal, the middle trace is the analogue signal of displacement, and

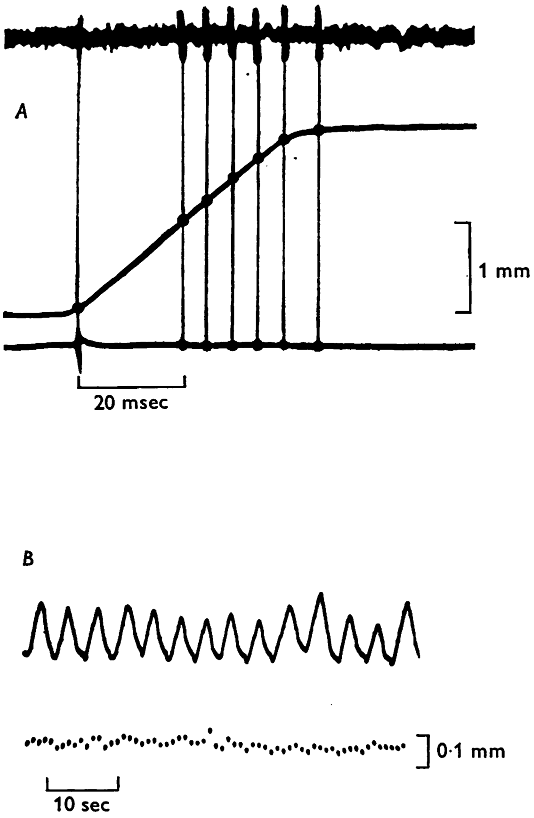

Fig. 2. *A*, display of a test sequence as filmed from an oscilloscope screen and used for measurements of latency, interspike intervals, stimulus amplitude and contact point height. The upper trace shows the nerve signal, the middle trace is the analogue signal of displacement of the stimulator probe, and the lower trace shows the contact pulse. One beam was split into three by a chopper amplifier and it was intensified by the contact pulse and the nerve impulses, giving the points and the corresponding vertical lines. *B*, variations of the contact pulse height synchronous with respiration. Upper trace is an analogue signal of the respiratory movements. Inspiration upwards. Lower trace shows the height of the contact point.

the lower trace shows the contact pulse, which is also visible as a deflexion in the nerve trace. In this display the nerve record as well as the record of the stimulus are intensified both by the contact pulse and the nerve impulses. A chopper amplifier was employed which gave rise to vertical lines which facilitated the measurement of the time intervals. The latency and interspike intervals were measured on the film under 10 × magnification with a resolution of 0·1 msec. For each stimulus the duration of the rising phase, the total amplitude and the position of the contact pulse were also measured and the effective stimulus amplitudes were deduced.

Data for stimulus–response functions were obtained by running series of stimuli of varying indentation velocities. Each velocity was repeated 2–3 times. For the majority of the units the stimulus–response relation was constructed from a single series of stimuli presented in descending order of displacement velocities from maximum to threshold velocity. For a few units the recording situation allowed for additional series with stimuli in ascending or descending orders of velocities. The data obtained from the records were processed with the aid of a programmable desk calculator (Hewlett Packard 9800 A).

RESULTS

In the present series of experiments a total of 150 afferent units in the ulnar and median nerves were studied. Of these 101 (67 %) were slowly adapting receptors which will be described in a subsequent paper. The present paper is concerned with 49 (33 %) of the receptors, which were all rapidly adapting in the sense that a nerve discharge was evoked exclusively during the rising or falling phase of skin indentation. The predominance of slowly adapting receptors in the present sample is in agreement with the findings in an earlier report (Knibestöl & Vallbo, 1970).

The rapidly adapting receptors in the present sample could readily be divided in two groups on the basis of the nature of the receptive fields: RA-receptors which have rather small receptive fields with relatively distinct borders, and PC-receptors which have much larger fields with indistinct borders, sometimes with a central point or area of maximal sensitivity. Thirty-nine units or 26 % of the total sample were classified as RA-receptors, and ten units or 6·7 % of the total sample were classified as PC-receptors, confirming the relative rarity of PC-receptors reported in an earlier study (Knibestöl & Vallbo, 1970).

RA-receptors

Receptive fields and thresholds. The thirty-nine receptors in this group were located in the glabrous skin area of the palm and the volar aspects of the fingers, but for some units the receptive fields extended partly to the lateral aspects of the fingers. In Fig. 3*A* the location and extent of thirty-two fields are presented in a semischematic drawing, and below is shown the frequency distribution of the field sizes for the same units. The distribution is positively skewed with a range from 6 to 208 mm^2 and a mean of 54·9 ± 8·6 (S.E. of the mean). With regard to the field sizes the mean was smaller for the endings located on the distal phalanx compared with the endings located in the palm (39·3 ± 7·5 and 75·3 ± 24·1 respectively), but the difference was not statistically significant ($P > 0·05$, Wilcoxon's test).

The amplitude and the velocity thresholds for the RA-receptors are presented in Fig. 4*A*, *B* (upper parts) as frequency distribution histograms. For the majority of the units (73 %) amplitude thresholds were less than 0·5 mm, but only two units (7·7 %) had thresholds below 0·1 mm; no single unit had a threshold below 50 μm. For three units the amplitude threshold was measured at several points within as well as outside the receptive

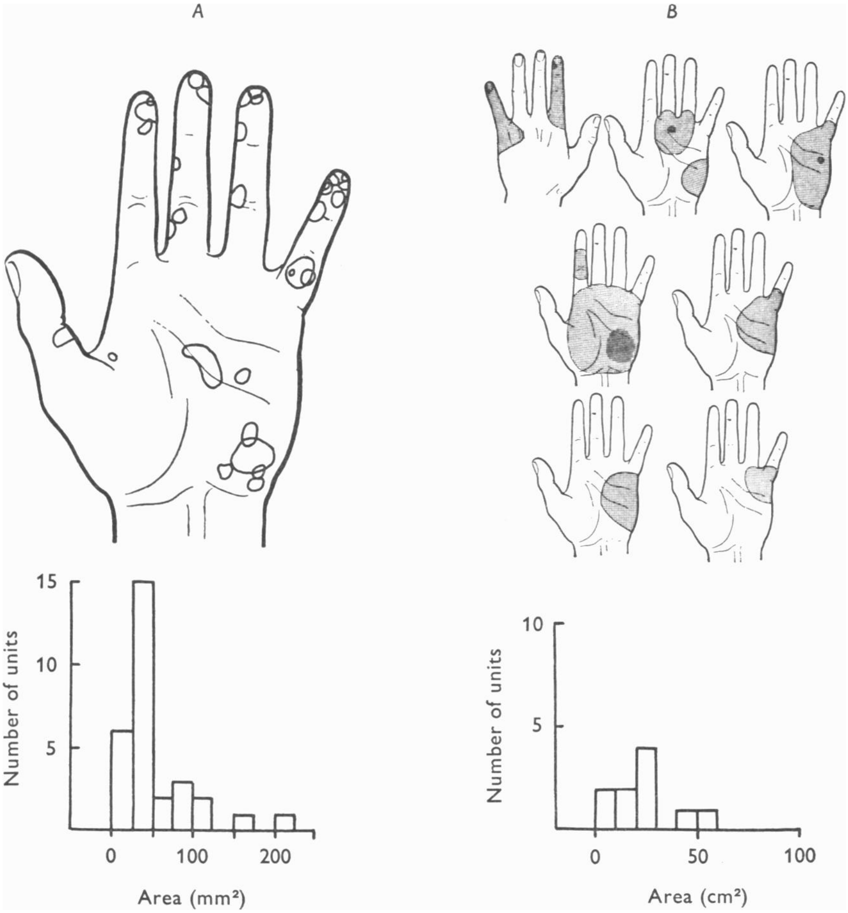

Fig. 3. Schematic drawings of receptive fields. *A*, RA-receptors. *B*, PC-receptors. Below are given histograms showing the distribution of the receptive field sizes.

field as mapped manually with near-threshold stimuli (see Methods). An example is given in Fig. 5*A*, where it may be seen that the threshold is uniform within the field, but outside there was a rather steep rise of the threshold with the distance from the field borders. The rise was steeper in the transverse direction than it was in the longitudinal direction of the finger. The mechanical properties of the skin may well account for this, as it was seen that the dimpling of the skin produced by an indentation extended further in the longitudinal than in the transverse direction.

The velocity thresholds varied considerably, from 0·4 to 39·3 mm/sec (Fig. 4*B*), but most of the units (78 %) had a velocity threshold below

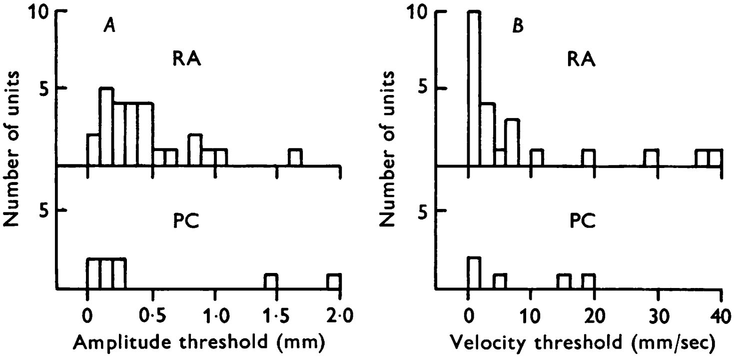

Fig. 4. Frequency distributions of amplitude thresholds (*A*), and velocity thresholds (*B*). Upper part RA-receptors, lower part PC-receptors.

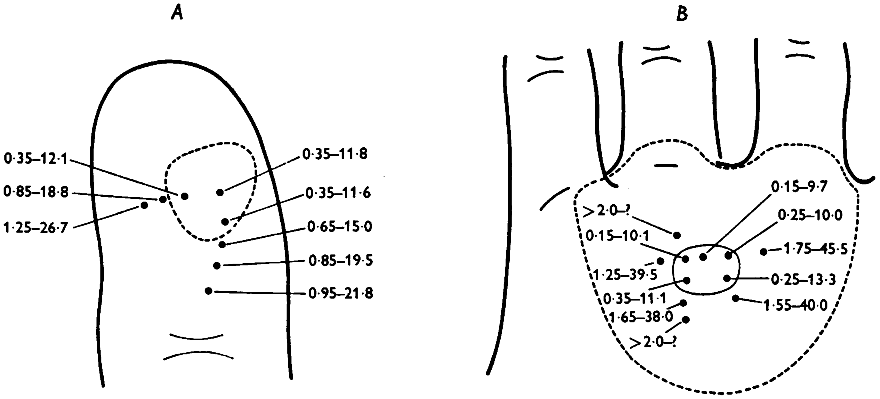

Fig. 5. Amplitude thresholds and latencies at different sites in relation to the receptive fields. For each point two numbers are given, the first one indicating amplitude threshold in mm, the second one indicating latency in msec. Interrupted lines show the receptive field borders. *A*, A RA-receptor field on the fifth finger. *B*, A PC-receptor field in the palm.

8 mm/sec. There was a positive correlation between amplitude thresholds and velocity thresholds for the RA-receptors ($r = 0{\cdot}68$, $n = 22$).

Latencies and conduction velocities. The stimulus–response latencies were measured with the purpose of calculating the average conduction velocity of the afferent nerve fibre of the individual sensory unit. For all the units there was an extensive range of supra-threshold stimuli over which the latency was constant, but near the threshold there was a latency increase of varying degree from one unit to the other, as is also well known from studies on animals (e.g. Gray & Malcolm, 1950; Lindblom, 1958; Catton, 1966).

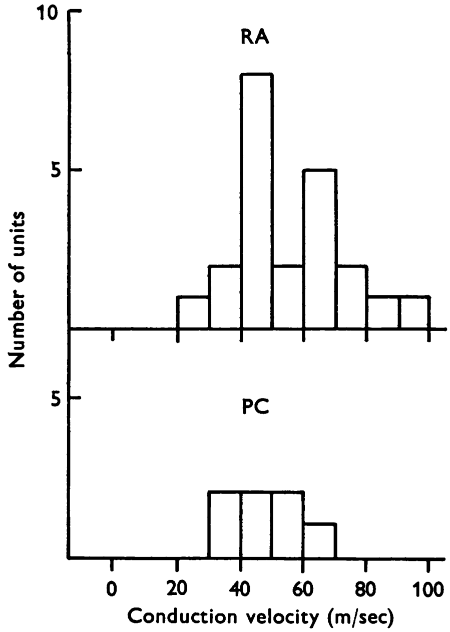

Fig. 6. Conduction velocities of twenty-two RA-receptor afferents (upper part) and seven PC-receptor afferents (lower part).

The minimal latency was fairly uniform within the receptive field, but it increased outside the field (see Fig. 5*A*). The conduction velocities based on minimal latencies at the centre of the receptive field, corrected for amplitude thresholds (see Methods), are shown in the histogram in Fig. 6 (upper part). The distribution is unimodal with a range from 26 to 91 m/sec, and a mean of 55·3 ± 3·4.

General discharge characteristics. The recordings of Fig. 7 show examples of the discharge from two units at different indentation velocities. The two units demonstrate somewhat different patterns of discharge. Many units, like the one in Fig. 7*A*, responded with only a few impulses and the

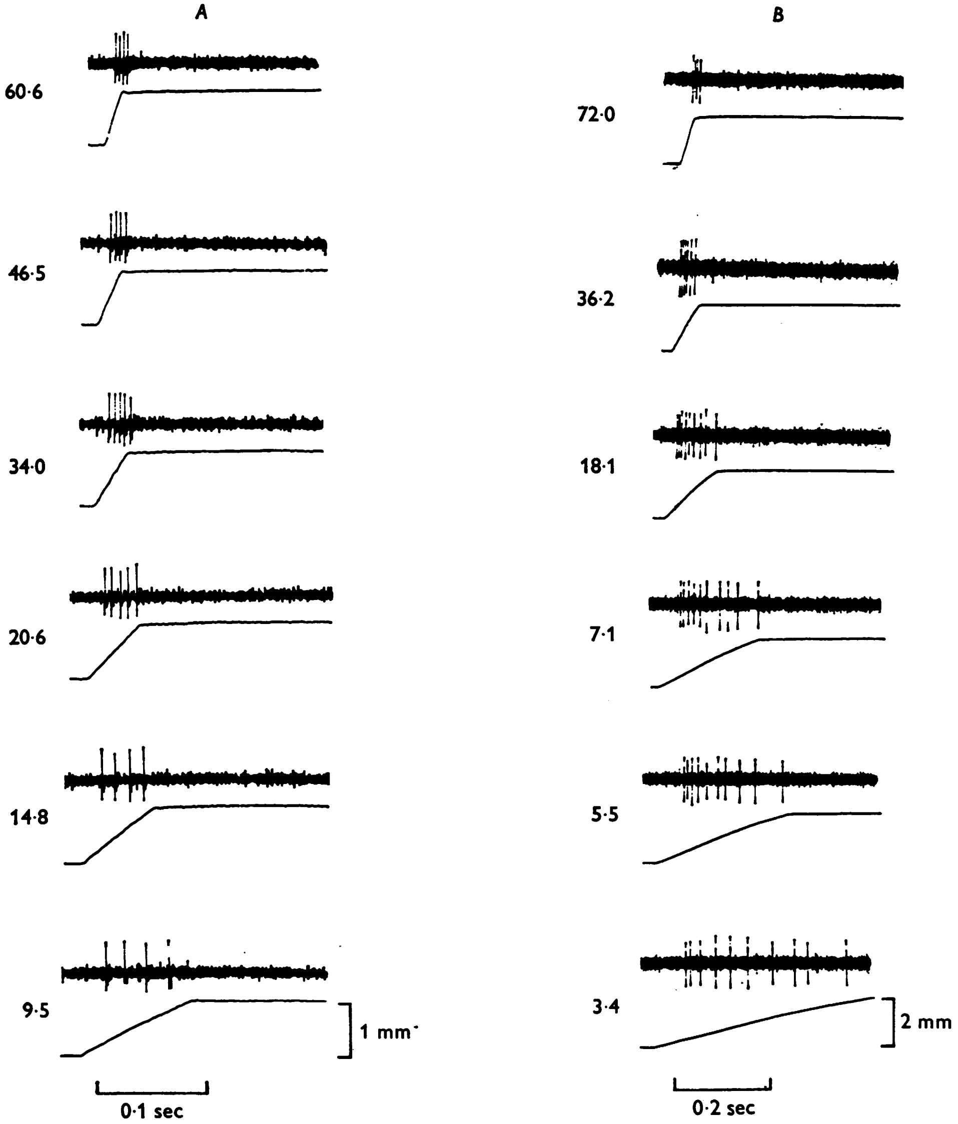

Fig. 7. Discharge patterns of two RA-receptors at different indentation velocities. The numbers to the left give the velocities in mm/sec. *A*, a unit which responded with nearly constant number of spikes at all velocities and with interspike intervals of nearly uniform lengths at a given indentation velocity. *B*, a unit which responded with an increasing number of spikes as the velocities decreased and with a progressive lengthening of the interspike intervals at a given indentation velocity.

number was nearly constant at all velocities. Other units, like the one in Fig. 7*B*, responded with numerous impulses, and the number increased with decreasing velocities of indentation. These two units also differ somewhat in another respect, concerning the relative length of the inter-spike intervals in a series of impulses. In the unit in Fig. 7*A* all the inter-spike intervals at a given velocity were of nearly constant length, whereas in the unit in Fig. 7*B* there was a progressive lengthening of consecutive intervals in a series. The latter pattern was more commonly seen in units with numerous impulses. There was, however, no indication that these two patterns represented two different receptor types. This may be seen in Fig. 8 where the number of spikes is plotted as a function of indentation velocity for a representative sample of units. The abscissa is logarithmic in order to compress the scale. As may be seen there is rather a continuous spectrum between, on the one hand, units with few impulses, the number being constant or decreasing with decreasing velocity, and on the other hand units with many impulses where the number increased up to a maximum as the velocity was lowered, decreasing again as the velocity threshold was approached.

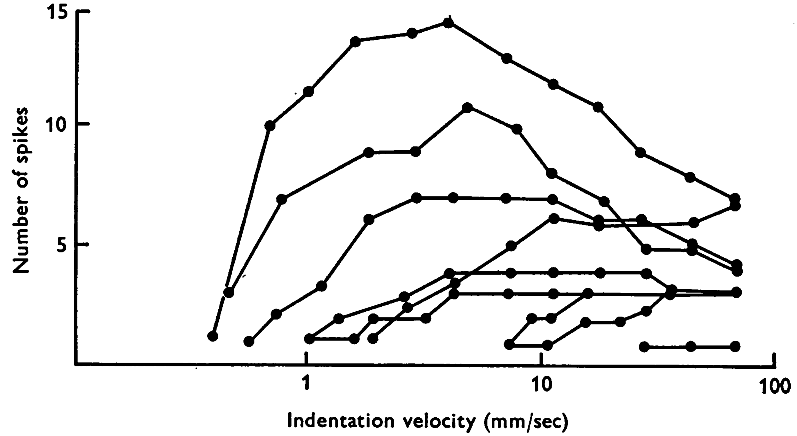

Fig. 8. Relation between number of spikes and indentation velocity for nine RA-receptors.

Stimulus–response relations. Data suitable for a quantitative analysis of the stimulus–response relation were collected from nineteen units. In Fig. 9*A* is shown the result from one representative unit, where the mean nerve impulse frequency is plotted against indentation velocity. All the other units exhibited similar negatively accelerating velocity–frequency plots, although there was a considerable variation in detail with regard to the shapes of the curves and the maximal frequencies. As a simple power function of the general form $R = aS^b$ is the most generally reported stimulus–response function for cutaneous mechanoreceptors, the data were replotted on log-log co-ordinates (Fig. 9*B*). It can be seen that there is a systematic deviation from the straight line representing the best fitting power function, and this tendency was evident for all other units studied. In Fig. 9*C* the data are replotted on semilogarithmic co-ordinates. The symmetric sigmoid curve appearing in this plot suggested that the hyperbolic tangent log function first used by Naka & Rushton (1966) to describe the S-potentials of the fish retina could be an adequate description

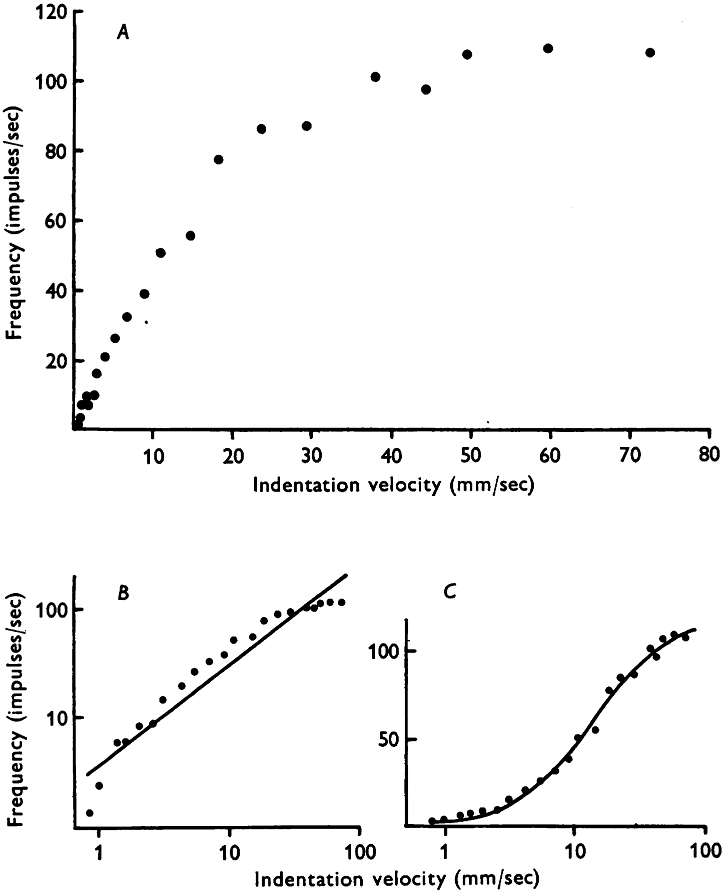

Fig. 9. Stimulus–response functions of a RA-receptor. *A*, data plotted on linear co-ordinates. *B*, the same data plotted on log-log co-ordinates. The straight line is the best fitting power function ($r = 0{\cdot}96$). *C*, the same data on a semilogarithmic plot. The curve is the best fitting log tanh function ($r = 0{\cdot}99$).

of the stimulus–response function for the present type of receptors. This assumption was tested by making use of a transformation of the equation of Naka and Rushton allowing linear regression analysis. Naka and Rushton proposed that the relation between the intensity of a light flash, I, and the receptor response measured as the amplitude of the resulting S-potential, V, followed the equation

$$V/V_{\mathrm{m}} = I/(I+I_{\frac{1}{2}}), \tag{1}$$

where V_{m} is the maximal, asymptotic value of V and $I_{\frac{1}{2}}$ is the value of I at which V is half of its maximum. If mean nerve impulse frequency (R) and indentation velocity (S) are substituted for V and I in eqn. (1) and R/R_{m} is plotted against $\log S$, writing $J = \log S$ and $d = S_{\frac{1}{2}}$, then eqn. (1) becomes

$$R/R_{\mathrm{m}} = 1/(1+d\,\mathrm{e}^{-kJ}), \tag{2}$$

where k is a constant. Eqn. (2) can be transformed to a linear form which is suitable for curve fitting (Stratten & Ogden, 1971):
Let $d = \mathrm{e}^{-2a}$ and $k = 2b$, then

$$R/R_{\mathrm{m}} = 1/(1+\mathrm{e}^{-2(a+bJ)}).$$

Let $a+bJ = w$, then

$$R/R_{\mathrm{m}} = 1/(1+\mathrm{e}^{-2w}) = \mathrm{e}^{2w}/\mathrm{e}^{2w}+1$$

$$= \tfrac{1}{2}+\tfrac{1}{2}\frac{\mathrm{e}^{w}-\mathrm{e}^{-w}}{\mathrm{e}^{w}+\mathrm{e}^{-w}},$$

$$R/R_{\mathrm{m}} = \tfrac{1}{2}+\tfrac{1}{2}\tanh w, \tag{3}$$

which is the log hyperbolic tangent function of Naka & Rushton (1966). Substituting for w and J gives

$$R/R_{\mathrm{m}} = \tfrac{1}{2}+\tfrac{1}{2}\tanh(a+b\log S), \tag{4}$$

which is equivalent to

$$\tanh^{-1}(2R/R_{\mathrm{m}}-1) = a+b\log S. \tag{5}$$

This is the required linear equation.

The asymptotic frequency value R_{m} was not available from the data, but it was possible to calculate, for the individual unit, an R_{m} value which would give the best fitting log tanh curve. An R_{m} value was estimated from the general form of the curve and it was then successively adjusted until a particular R_{m} was found which provided the highest correlation coefficient. The result is shown in detail for one unit in Fig. 10, with the semilogarithmic plot in the upper part, and the linearized plot according to eqn. (5) in the lower part. It is seen that the fit of the optimal log tanh curve (with $R_{\mathrm{m}} = 278$) is nearly perfect, as also revealed by the high correlation coefficient of 0·999.

In Fig. 11*A* data from all the nineteen units are shown on the same type of semilogarithmic plot as in Fig 9*C*. The points from the individual units are arbitrarily shifted along the x-axis to have them well separated in order to facilitate the inter-unitary comparison. Concerning the general form of the stimulus–response relations in this plot, it may be seen that for at least six units a more or less distinct S-shaped curve was described by the points. For the other units the impulse frequency increased with log velocity at an accelerating rate in the lower part, approaching a more or less linear course in the upper part, whereas there was no evidence of frequency saturation at the highest velocities. For all these sixteen units the

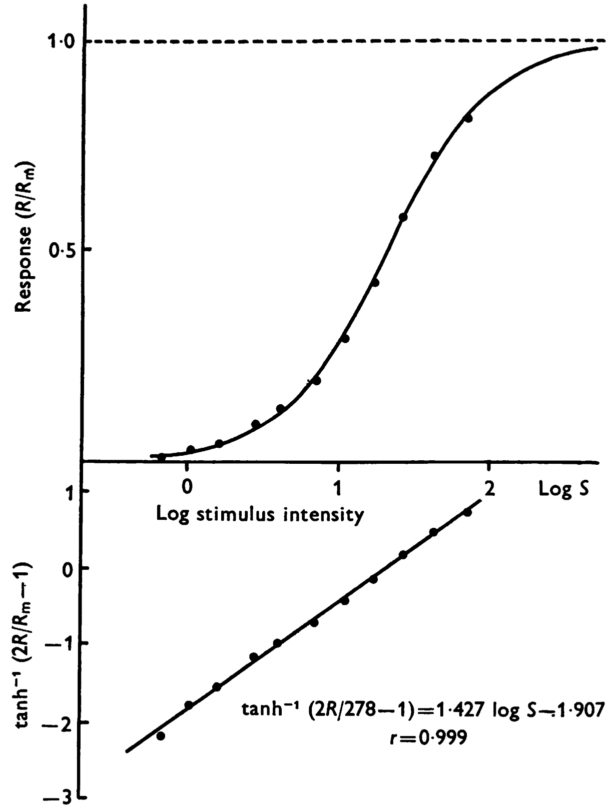

Fig. 10. Display to illustrate the regression analysis of the stimulus–response function for a RA-receptor. Upper part shows the data plotted on semilogarithmic coordinates. Abscissa: log indentation velocity. Ordinate: normalized nerve impulse frequency. The upper asymptote, interrupted line, corresponds to a calculated R_m of 278 impulses/sec. Lower part shows the data plotted according to eqn. (5) (see text). Abscissa: log indentation velocity. Ordinate: $\tanh^{-1}(2R/R_m - 1)$. The straight line is the regression line fitted according to eqn. (5).

log tanh curve was the best description of the stimulus–response function. For the remaining three units a pure logarithmic function was the best description. The results of the regression analysis are summarized in Table 1, where the best fitting functions and the correlation coefficients and parameters of the fitted curves are given. For the units best described by the log tanh function, the calculated asymptotic frequency values, R_m, are also given. The best fitting log tanh and logarithmic curves are entered over the data points in the diagram in Fig. 11*A*. As is seen the fit is very close for all the units, as is also evident by the high correlation coefficients which are 0·99 or better for the majority of units.

TABLE 1. Stimulus–response functions for RA-receptors and PC-receptors in human glabrous skin area. R_m = asymptotic frequency value, a and b = constants of best fitting functions (log tanh function, $R/R_m = \frac{1}{2}+\frac{1}{2}\tanh(a+b\log S)$, logarithmic function, $R = a+b\log S$), r = correlation coefficient

Unit	Function type	a	b	R_m	r	Curve slope
RA-receptors						
12–5–3	log tanh	−4·363	3·011	377	0·997	567·68
24–2–3	log tanh	−3·968	2·661	326	0·998	433·81
2–6–7	Logarithmic	−420·26	369·64	—	0·990	369·64
13–5–2	log tanh	−2·762	1·668	378	0·999	315·41
11–6–2	Logarithmic	−347·90	305·52	—	0·996	305·52
24–2–5	log tanh	−2·444	1·677	360	0·996	301·84
16–6–3	log tanh	−2·910	1·634	349	0·992	285·16
2–6–10	Logarithmic	−234·92	231·53	—	0·976	231·53
15–5–4	log tanh	−2·215	1·170	378	0·998	221·23
12–5–5	log tanh	−2·882	1·761	241	0·990	212·17
2–6–8	log tanh	−1·907	1·427	278	0·999	198·38
12–5–4	log tanh	−2·878	1·657	238	0·971	197·26
11–5–5	log tanh	−2·148	1·514	257	0·994	194·63
12–5–1	log tanh	−2·232	1·346	260	0·999	175·08
16–6–4	log tanh	−2·404	1·529	219	0·996	167·42
11–6–8	log tanh	−1·716	1·247	258	0·997	169·87
16–6–6	log tanh	−2·069	1·328	221	0·997	146·81
16–6–7	log tanh	−2·005	1·225	147	0·994	145·78
21–4–4	log tanh	−1·895	1·657	120	0·995	99·41
PC-receptors						
29–4–1	log tanh	−2·172	1·322	533	0·999	352·30
15–5–3	log tanh	−1·869	1·209	406	0·998	245·62
26–5–2	Logarithmic	−125·68	194·12	—	0·978	194·12
11–5–2	Logarithmic	−40·43	43·15	—	0·985	43·15

The curves in Fig. 11*A* are arranged in order of decreasing slope from left to right. For the logarithmic curves the slope is given by the parameter b of the regression line (see Table 1). For the log tanh curves a numerical expression for the slope may be obtained by calculating the first derivative

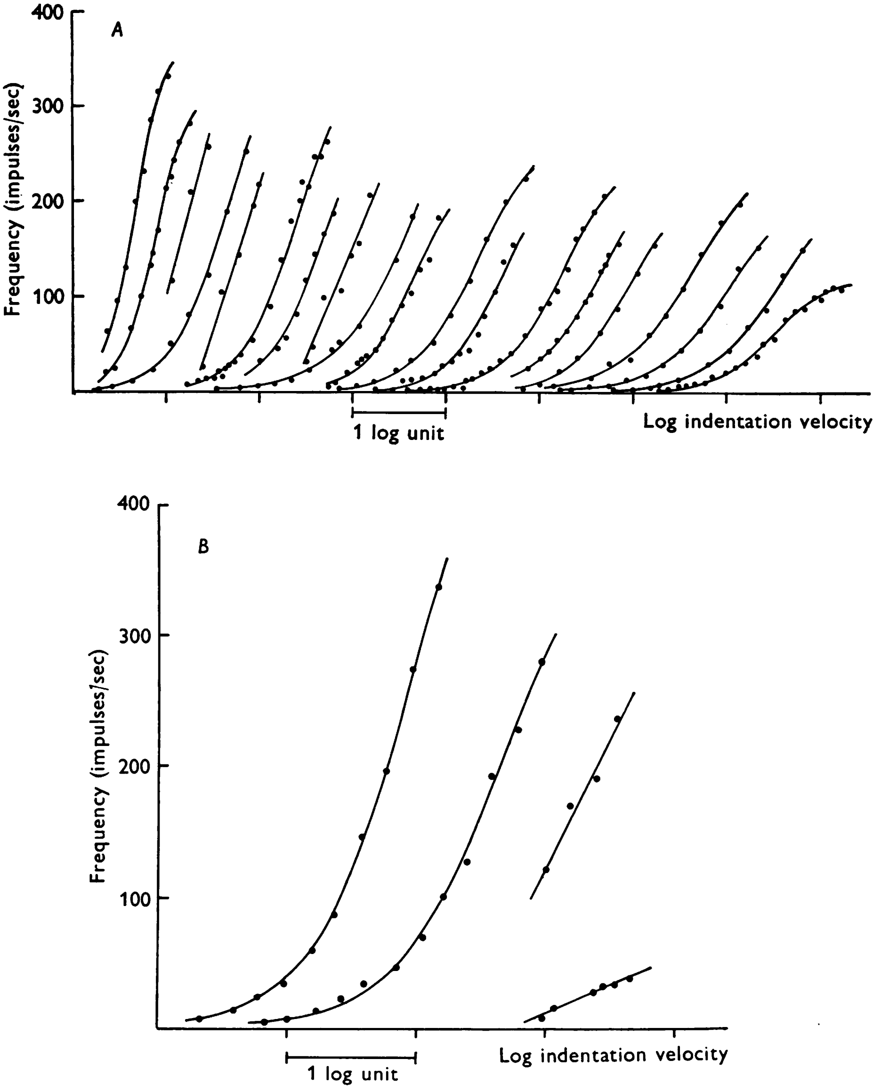

Fig. 11. Stimulus–response functions of nineteen RA-receptors (*A*) and four PC-receptors, *B*, the abscissa represents indentation velocity on a logarithmic scale, and the ordinate nerve impulse frequency on a linear scale. The individual plots are arbitrarily shifted along the abscissa. The curves entered over the points are the best fitting log tanh functions or logarthmic functions.

which has a maximum at the symmetry-point where $R/R_{\mathrm{m}} = \frac{1}{2}$. From eqn. (2) is obtained

$$\frac{\mathrm{d}}{\mathrm{d}J}(R/R_{\mathrm{m}}) = k(R/R_{\mathrm{m}})(1-R/R_{\mathrm{m}}).$$

If $R/R_{\mathrm{m}} = \frac{1}{2}$, then

$$\frac{\mathrm{d}}{\mathrm{d}J}(R/R_{\mathrm{m}}) \max = k/4 = \tfrac{1}{2}b.$$

Thus, $\frac{1}{2}b$ is the maximal slope of the log tanh curves on the normalized ordinate scale, while $R_{\mathrm{m}}\frac{1}{2}b$ is the maximal slope in the non-transformed ordinate scale according to which the data are presented in Fig. 11. The numerical values of the slopes as defined here are entered in Table 1. It may be seen from Fig. 11*A* that the slope of the curves is apparently related to the maximal frequency as determined experimentally, this being higher the higher the slope. However, the maximal frequency found experimentally was for many units obviously limited by the maximal indentation velocity which the stimulator could provide. The calculated asymptotic frequency values R_{m}, which may be a better estimation of the frequency saturation level for the units, did not show any obvious relation to the slope of the curves. It may be noticed that none of the units had an estimated maximal frequency above 400 impulses/sec.

From Fig. 11*A* it can also be seen that for the units with low curve slope the experimental points were in general distributed over a broader range of velocities compared with the units with high slope. This feature is related to the fact that units with high slope in general had higher velocity thresholds than units with low slope. It is also seen that the approximately linear section of the curves around the symmetry-point tends to be more conspicuous in curves with high slope. Actually the three purely logarithmic curves are found in the left side of the diagram, and for the two curves to the far left the differences in correlation coefficients for a logarithmic function and the log tanh function were very small and not statistically significant. These facts indicate that the logarithmic function can probably be regarded as a special case of the more general log tanh function, appearing in units with high curve slope with approach towards linearity.

PC-receptors

The ten units classified as PC-receptors had large receptive fields, with rather indistinct borders. The approximate boundaries were determined, outside of which no discharge would be elicited by fairly strong rapid taps. The fields determined in this way are shown in Fig. 3*B*. The field areas ranged from 4 to 44 cm^2 (see histogram below in Fig. 3*B*), and thus they were an order of magnitude larger than the fields of the RA-receptors. The approximate location of the end-organ could be determined in some units, as there was a central point or small area of very high sensitivity. Fig. 5*B* shows the excitability profile of such a field, where the encircled points in the centre all have low thresholds and short latencies and thus probably are close to the end organ, whereas the points outside this area have increasingly higher thresholds and latencies with increasing distance from the central area. In another three units a similar small area of maximal sensitivity could be defined and in one unit a somewhat wider area with higher sensitivity could be distinguished (black dots and dark stippled area respectively in Fig. 3*B*), whereas in the remaining units no such area could be clearly recognized.

Threshold data are presented in Fig. 4*A* and *B* (lower parts). Two units had very high amplitude thresholds, whereas the majority had low thresholds, ranging from 50 to 250 μm. One receptor had an extremely low threshold which could not be adequately measured; it was certainly below 50 μm. The velocity thresholds were determined for five units, and no difference was found in relation to the velocity thresholds of the RA-receptors: examples of both low and relatively high velocity thresholds were encountered. Conduction velocities estimated for seven PC-receptors ranged from 34 to 61 m/sec. with a mean of $46{\cdot}9 \pm 3{\cdot}5$ (Fig. 6, lower part).

Examples of discharge from PC-receptors are given in Fig. 12. As seen in Fig. 12*B* and *C* there was a great variability in the number of spikes elicited from one unit to the other. All the PC-units exhibited an off-discharge, which was often very conspicuous, comprising four to six nerve impulses. In comparison only 50 % of the RA-receptors discharged at off, and usually not more than one or two impulses. As a group the discharge from PC-receptors was more irregular than the discharge from RA-receptors. Some of the PC-units exhibited discharge characteristics which could not be related to the characteristics of the stimulus in a simple way. An example is shown in Fig. 12*A*. A long sequence of nerve impulses, sometimes as many as twenty, was discharged during the first part of the plateau phase of the stimulus, and also at off. The nerve impulse frequency during the bursts was remarkably constant and regular, and it was completely independent of indentation velocity and amplitude. Only one unit was seen with this type of discharge pattern. Another peculiar type of discharge is demonstrated by the unit in Fig. 14*D*. It is seen that there is a progressive shortening of the last interval with decreasing amplitudes, and it may be noticed that the last nerve impulse appears after a nearly constant latency from the transition between the moving phase and the plateau phase. A similar phenomenon was observed in another two PC-units, but it was never seen in the RA-units.

As already stated, the discharge of PC-receptors was generally rather irregular and was often poorly related to the characteristics of the stimulus. However, in four units, the frequency was clearly related to the velocity of skin indentation, and stimulus–response curves could be constructed. These are given in Fig. 11*B*, and the best fitting type of function and parameters of the curves are given in Table 1. One unit had an irregular discharge with mean frequency only increasing to a limited degree with increasing velocity, indicating a rather poor sensitivity to indentation velocity. As seen from Fig. 11*B* three of the units had curve slopes, and thereby sensitivity to indentation velocity, comparable to most of the RA-receptors. Two units had stimulus–response curves of the log tanh type, and two units had a logarithmic function best fitting the data points. It is also worth noticing that the calculated upper asymptote for the two units with a log tanh type of function was above 400 impulses/sec, in contrast to the RA-receptors (see Table 1).

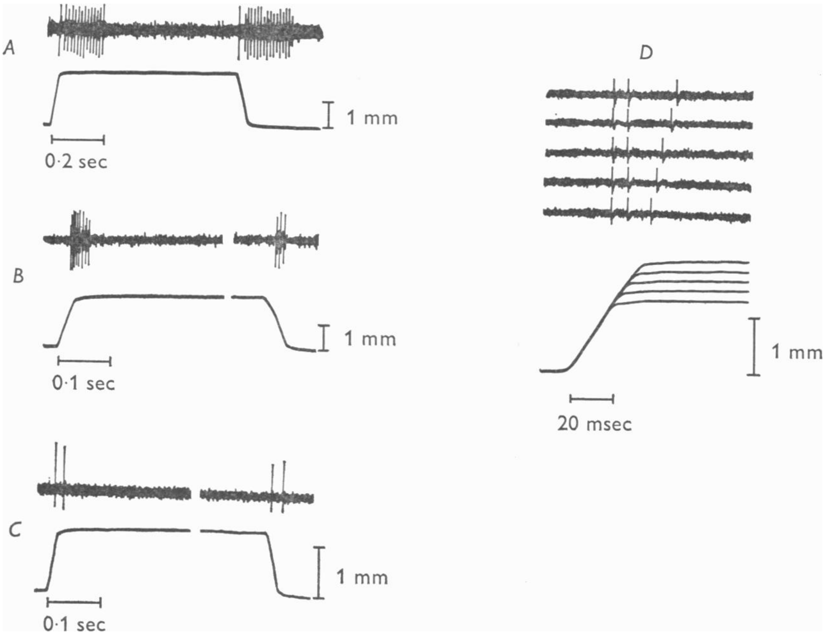

Fig. 12. Discharge patterns of PC-receptors. *A*, a unit showing long bursts of impulses both at on and off (after-oscillations). *B*, a unit responding with many impulses during identation, and *C*, a unit responding with only a few impulses. *D*, a unit showing shortening of the last interspike interval on reduction of indentation amplitude. The upper traces show the nervous discharge for five amplitude levels in descending order downwards, and the lower traces show the analogue signals of the corresponding stimuli.

DISCUSSION

The findings of the present study confirm the conclusion arrived at in an earlier report (Knibestöl & Vallbo, 1970) that the rapidly adapting mechanoreceptors in the human glabrous skin area fall into two distinct groups, and that these two types of receptors have similar properties as the RA-receptors and PC-receptors respectively found in the glabrous skin area of other primates (Lindblom, 1965; Lindblom & Lund, 1966; Talbot *et al.* 1968). The most striking difference between the two types is the nature of the receptive fields: the RA-receptors have small fields with distinct borders, while the PC-receptors have large fields with indistinct borders. The present sample of receptors were classified on the basis of the field characteristics, and the classification was quite unequivocal. In the RA-receptor group, two somewhat different types of discharge patterns were found, but further analysis gave no evidence that they represented two different receptor types. Talbot *et al.* (1968) observed a similar difference in RA-receptors in the monkey glabrous skin, but it was not implied by these authors that two different receptor types were involved. Other differences between RA- and PC-receptors than the differences in receptive fields are known from animal studies, but were not analysed in detail in the present study. Thus PC-receptors in general have the capacity to respond with higher impulse frequencies than RA-receptors, and have also a higher sensitivity to vibratory stimuli in the high frequency range (Lindblom & Lund, 1966; Talbot *et al.* 1968). It may be significant in this respect that the calculated maximal frequencies were higher for the PC-receptors than for the RA-receptors. Some special types of discharge patterns exhibited by the PC-receptors may also be associated with the high sensitivity of these receptors to vibratory stimuli, e.g. the type of discharge seen in Fig. 12*A*. Lindblom & Lund (1966) found a similar pattern in twelve out of forty PC-receptors in the monkey, and suggested that this type of discharge may be due to repeated excitation by afteroscillations or complex interference phenomena in the deeper tissue layers. A similar explanation may be invoked for the interval shortening on decreasing amplitude shown by some PC-receptors. As discharge patterns of these types were exclusively exhibited by the PC-receptors, they may, when encountered, serve as additional criteria for distinguishing the PC-receptors from the RA-receptors.

The type of end-organ corresponding to RA-receptors and PC-receptors as defined physiologically have not been conclusively identified in the primates, but Lindblom & Lund (1966) have shown that in the monkey the RA-receptors are localized intracutaneously and the PC-receptors are localized in the subcutaneous tissues. They further summarized all the evidence that the only end-organ known with the combination of properties exhibited by the wide-field receptors is the Pacinian corpuscles. More recently Lynn (1969, 1971) has provided more direct evidence on this point for the homologous glabrous skin area of the foot pad of the cat, where the same separation in wide-field (PC-receptors) and small-field receptors (RA-receptors) can be recognized. As to the RA-receptors, recent evidence indicates that the Meissner corpuscles are the end-organ corresponding to this receptor type (Jänig, 1971; Munger, 1971). Both Pacinian corpuscles and Meissner corpuscles are known to be abundant in the glabrous skin area both in man and other primates. Pacinian corpuscles are found both in superficial and deeper layers of the subcutaneous adipose tissues, as well as in association with deeper structures such as the palmar aponeurosis and the digital tendon sheaths (Stilwell, 1957; Quilliam & Ridley, 1971). Meissner corpuscles are abundant in the dermal papillae of human glabrous skin (e.g. Cauna, 1954; Bolton, Winkelmann & Dyck, 1966), and are located at a depth beneath the epidermal surface varying between 100 and 500 μm (Quilliam & Ridley, 1971).

The amplitude thresholds for both types of receptors in the human glabrous skin were on the average considerably higher than those for the corresponding receptors in the monkey, where both types have thresholds below 100 μm (Lindblom, 1965; Lindblom & Lund, 1966), whereas in the present study only a small proportion of the receptors had thresholds in this range. The difference between the two species in this respect may be related either to differences in mechanical or structural properties of the skin, e.g. thickness of the skin, or to differences in the excitability properties of the receptors themselves. Further, in the monkey the PC-receptors have significantly lower amplitude thresholds than the RA-receptors (range less than 5–30 μm for the PC-receptors and 10–80 μm for the RA-receptors, Lindblom, 1965; Lindblom & Lund, 1966) and this was also the case in the cat foot pad (Jänig, Schmidt & Zimmermann, 1968). The data from the present sample did not allow any safe conclusion as to a similar difference between the two types in the humans, but the possibility that a difference might be revealed in larger samples cannot be excluded. The rather large range of variation of the thresholds for both types of receptors may be related to several factors, e.g. the location and depth beneath the skin surface of the end organs (see above).

On the basis of the significant difference in thresholds for the two types of receptors in the monkey, Lindblom (1965) assumes that the PC-receptors rather than the RA-receptors are responsible for the threshold sensation of touch, referring to older studies by Fessard (1930), indicating that the subjective threshold on the fingers may be as low as a few microns. The findings in the present study would seem to support this assumption to some extent, as the thresholds for the RA-receptors in general were substantially higher than those of the monkey and none had threshold below the 50 μm level, whereas at least one PC-receptor had a threshold below this level. However, claims of a subjective threshold of this extremely low magnitude must be interpreted with caution in view of the difficulties encountered in controlling the effective stimulus amplitude, due to movements of the skin surface, which may amount to at least 30 μm, even with proper attention to rigorous fixation of the limb. Apart from this, it appears that in the studies of Fessard the experimental conditions were quite different from those of the present study; Fessard measured the subjective threshold for rapid indentations superimposed upon a comparatively large steady indentation, the latter being up to hundred times larger than the rapid test indentations. It is conceivable that the threshold as defined by Fessard is considerably lower than the threshold measured as absolute skin indentation with rectangular mechanical stimuli. Extensive studies of subjective thresholds for touch have later been done by Weinstein (1968) using von Frey hairs calibrated for force, but unfortunately the data obtained by this method does not allow for direct comparison with those obtained in the present study. It seems that the whole problem of the subjective threshold for touch should be re-investigated with an effort to control the effective stimulus amplitudes used.

In the monkey the PC-receptors generally have higher velocity thresholds than the RA-receptors (Lindblom & Lund, 1966). No such difference could be clearly demonstrated in the present study, but the samples are too small to allow any safe conclusion on this point. The conduction velocities indicate that all the receptors studied are supplied with large myelinated nerve fibres in the A alpha-beta range. No difference could be demonstrated between the two groups of receptors units. The present data are in fairly good agreement with the figures given for sensory conduction velocities in median and ulnar nerves of young adult humans measured from the compound action potential (51–56 m/sec from finger to wrist, and 60–65 m/sec from wrist to elbow; see Buchtal & Rosenfalck, 1966).

For the majority of receptors in the present study, the log tanh function (Naka & Rushton, 1966; Lipetz, 1969, 1971) gave the best description of the stimulus–response relationship over the total range of stimulus intensities, whereas an approximate logarithmic relation was valid only over a limited range of stimulus strength. For a minority of the receptors a logarithmic function was a more adequate description over the total range of experimental data. These were largely units which had high velocity thresholds and rather high slope of the stimulus–response curves. It may well be that the logarithmic form of the stimulus–response function is fortuitous and related to the limited range of stimulus velocities employed.

An extension to higher stimulus velocities may disclose an approach towards a frequency saturation also for these units, and an optimal description by a log tanh function. Since, as previously discussed, the end-organs corresponding to the PC-receptors are almost certainly the Pacinian corpuscles, it is of particular interest in this context that Lipetz (1969) has shown that the data obtained by Loewenstein (1961) from studies of the receptor potential of isolated Pacinian corpuscles as a function of direct pressure or activated membrane area can be well fitted by the log tanh function. The important fact to be noticed in this connexion is that this basic similarity of the transfer function between stimulus intensity and receptor output in the two studies seems to exist irrespective of the obvious differences between an isolated corpuscle with outer cores removed and the present conditions of the receptor in its natural environment with stimuli transmitted through overlying tissue layers.

Cutaneous mechanoreceptors have recently been extensively studied in many animal species, and in general a power function has been reported to be the best description of the stimulus–response relationship (Werner & Mountcastle, 1965; Mountcastle, Talbot & Kornhuber 1966; Brown & Iggo, 1967; Merzenich, 1968; Harrington & Merzenich, 1970; Pubols, Pubols & Munger, 1971), although a few exceptions to this rule have appeared (Lindblom, 1962, 1965; Kenton, Kruger & Woo, 1971). The question of the possible significance of this apparent discrepancy between human receptors and those studied in animals cannot be answered at present. There may exist real species differences in this respect, or the discrepancy may largely be accounted for by methodological differences, e.g. sequence of stimulus presentation (Kenton *et al.* 1971), or the range of stimulus intensities employed may be of importance. Thus, although Lindblom (1965) reports an essentially logarithmic stimulus–response function for RA-receptors in the monkey glabrous skin, the typical sigmoid shape on semilogarithmic plot for many of his units (see, for example, Fig. 8 in Lindblom, 1965) suggests that the log tanh function might be a better description over the total range of intensities.

Considering the relative roles in perception of the RA-receptors and the PC-receptors, it seems that the RA-receptors are particularly well suited for a frequency coding of the speed of skin indentation in view of the broad spectrum of receptors with varying velocity thresholds, sensitivity and maximal impulse frequency as demonstrated by the present sample. At one end of the spectrum movements of low velocity would largely activate receptors with a low velocity threshold, rather low sensitivity and low maximal frequency capacity, whereas in movements of high speed the nervous discharge would probably be dominated by receptors with rather high velocity thresholds, high sensitivities and relatively high maximal frequencies. The contribution from some PC-receptors in this respect cannot be excluded (see Fig. 11*B*), but it is equally clear that at least some PC-receptors cannot signal indentation velocity, as the discharge may be totally independent of this parameter of the stimulus. These receptors are, however, well suited for signalling vibratory movements, which may be the major role played in perception by the PC-receptors, especially vibrations in the high frequency range, whereas RA-receptors may have a role in perception of low-frequency vibrations (flutter), according to Talbot *et al.* (1968).

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