Mapping the Body Representation in the SI Cortex of Anesthetized and Awake Rats

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ABSTRACT

We have used single unit recording techniques to map the representation of cutaneous and joint somatosensory modalities in the primary somatosensory (SI) cortex of both anesthetized and awake rats. The cytoarchitectonic zones within the rat SI were divided into the following main categories: (1) granular zones (GZs)—areas exhibiting koniocortical cytoarchitecture (i.e., containing dense aggregates of layer IV granule cells), (2) perigranular zones (PGZs)—narrow strips of less granular cortex surrounding the GZs, and (3) dysgranular zones (DZs)—large areas of dysgranular cortex enclosed within the SI. The narrow strip between the SI and the rostrally adjacent frontal agranular cortex was termed the "transitional zone" (TZ).

Initial computer-based studies of the properties of cutaneous receptive fields (RFs) in SI showed that, although there were differences in response threshold, adaptability, frequency response, and overall RF size and shape of adjacent neurons, the size and location of the "centers" of the RFs were quite constant and were similar to those seen in multiple unit recordings. The same was true of RFs of single neurons recorded through different anesthetic states.

The body representation in SI was first mapped by determining single unit and unit cluster RFs within a total of 2,170 microelectrode penetrations in barbiturate-anesthetized rats. Cutaneous RFs in the GZs were quite discrete. Thus, a single, finely detailed, continuous map of the cutaneous periphery was definable within the GZs themselves. Only the forepaw had a double representation. RFs in the PGZs were larger and more diffuse, but since they covered roughly the same skin areas as the RFs in the most closely adjacent GZs, they fit into the same body map. Neurons in the DZs were unresponsive to any sensory stimuli in the anesthetized animal.

In chronically implanted, freely moving, awake animals cutaneous RFs were larger and more volatile than in the anesthetized, but the accuracy of the map was clearly preserved by the fact that the locations of the RF centers (which often must be defined quantitatively) were unchanged. The PGZs and DZs in the awake animals exhibited a multimodal convergence of cutaneous and joint movement RFs within single vertical penetrations, or even on single neurons. Directionally specific and bilateral cutaneous RFs were also observed in the DZs. It was concluded the DZs are more associative or integrative areas within the SI, but they could not be shown to comprise a distinct and separate body representation. The rat SI cortex therefore appears to contain, within a single overall body map, both granular and dysgranular cytoarchitectonic zones. Not only are different sensory modalities subserved within this map, but also different levels of physiological complexity and anesthesia sensitivity.

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The classic studies of Woolsey (‘58) constituted the first detailed investigations of the pattern of representation of the periphery in the mammalian somatic sensory cortex. These studies, which involved recording evoked potentials from the cortical surface, suggested that a single map of the body surface, with the hindlimbs oriented medially and the head laterally, was common to the primary somatosensory (SI) cortex of all mammals. More recent studies, involving unit cluster recording in anesthetized monkeys, have demonstrated multiple representations of part of the body surface in the region originally defined as the SI cortex (Paul et al., 1972; Merzenich et al., ‘78). These corresponded to the different cytoarchitectonic zones (areas 3a, 3b, 1, and 2) in the postcentral cortical region. To a large extent, cutaneous sensory modalities were found in areas 3b and 1, while areas 3a and 2 subserved deep somatic sensory modalities. A second body representation was definable in area 1 by virtue of the fact that it was oriented in a "mirror image" of the sinuimiscus in area 3b. Similar studies have been carried out in great detail in several primate species (Merzenich et al., ‘78; Kaas et al., ‘76; Nelson et al., ‘80), prosimians (Krishnamurti et al., ‘78; Sur et al., ‘80a), tree shrews (Sur et al., ‘80b), and cats (Dykes and Gabor, ‘81).

Rather complete maps of the cutaneous representation in the rat SI have been provided by Hall and Lindholm (‘74), and by Welker (‘71, ‘76), who demonstrated the advantages of using histological sections cut tangentially through layer IV from a flattened cortical hemisphere to visualize the structure of the entire cortex. A single representation of the cutaneous periphery was reported to reside in a complex array of "barrels" (cortical areas containing dense aggregates of layer IV granule cells), while no sensory representation was definable in the less granular cortical areas surrounding the barrels. Unfortunately, no clear delineation of the representation of noncutaneous somatosensory modalities in SI was provided in these rodent studies.

The first aim of this study was to construct a more detailed map of the representations of "cutaneous" (hair, skin, whiskers) and "joint movement" somatic sensory modalities in the SI cortex of the rat, and to define their relation to the cytoarchitectural zones within the SI. The existence of these sensory modalities in the SI cortex was first shown by Mountcastle (‘57) and Mountcastle and Powell (‘59). In reexamining this subject we have attempted to (1) precisely map the cutaneous representation in order to determine whether multiple representations are present, (2) determine what, if any, sensory representation exists in the dysgranular areas of the rat SI, and (3) define the representation of noncutaneous modalities.

Recently, McKenna et al. (‘81, ‘82) and Duncan et al. (‘82) have suggested that the apparent separation of the SI into different body representations may have resulted somewhat artifactually from the use of general anesthetics which are known to markedly reduce the sizes of cutaneous receptive fields (RFs). The use of multiple rather than single unit recordings was also implicated as a possible source of bias in favor of a uniformity of RF properties in given SI cortical regions.

The second major phase of this study involved a series of experiments designed to shed some light on these questions. Specifically, RFs of single and multiple units in awake and anesthetized animals were quantitatively analyzed to determine whether (1) the degree of RF homogeneity within simultaneously recorded neuronal clusters is sufficient for such a mapping study to be legitimate, and (2) if RFs defined in the anesthetized state are predictive of those defined in the awake state.

**METHODS**

**Recording in anesthetized animals**

Long Evans (Hooded) rats (250–350 gm) were anesthetized with pentobarbital (40–50 mg/kg B.W., I.P.) or Halothane (0.5–1.0% in oxygen, by continuous inhalation through tracheal intubation). Since RF sizes vary with anesthetic level, doses were kept at the minimum required to prevent any struggling or painful reaction on the part of the animal. When pentobarbital was used, small supplemental doses were administered when needed.

Anesthetized animals were mounted in a stereotaxic frame, and a relatively large (2–3-mm diameter) craniotomy was opened over the cortical area of interest using bregma as the initial point of reference. For recording in the lateral portions of the SI it was necessary to resect the temporalis muscle attached to the temporal crest. For recording in the most rostralateral locations the eyeball was also protracted with suture thread. Upon exposure of the cortex the dura was removed and the brain surface was covered with either warm saline or silicone oil. The blood vessel pattern on the cortical surface was drawn as reference coordinates for later in the experiment. For unit recording, glass microelectrodes (1–5 MΩ at 1 K Hz; filled with 2 M NaCl and fast green dye) were driven into the cortex with a Burleigh microdrive (Fishers, NY).

RFs were routinely determined by amplifying and filtering (bandpass from 5–5 K Hz) the recorded signal and listening to it through an audio speaker while using a fine-tipped probe to tap various skin areas lightly, or manipulate hairs and/or whiskers, until the zone responding most intensely and reliably was defined. Isolated single units were often monitored individually by listening to the TTL output pulse of a spike discriminator. In some experiments RFs were more quantitatively determined by generating poststimulus histograms of the average unit response to repetitive controlled mechanical stimulation of individual points within an array of locations on the skin. Three types of cutaneous stimuli were available to use: (1) punctate touch with a hand-held probe, (2) a servo-controlled programmable sinusoidal vibrating probe, and (3) electrocutaneous stimulation. When performed on the same cell these three techniques yield equivalent results (unpublished observations).

The hand-held probe, which was used most commonly here, featured an interchangeble selection of Von Frey-type wire probe tips, which were calibrated for different force levels of touch. These were connected to the inverting end of a 741-type op-amp which produced a TTL-compatible pulse to signal the time when the probe touched the (grounded) animal. Hairy skin was first shaved when this technique was used.

Poststimulus histograms of the response of single discriminated units to 20–50 repetitions of such stimuli were gen-
erated with a Data General Eclipse S-130 computer, displayed on a Tektronix 4012 Graphics Terminal, and stored on hard-copy with a Versatec printer-plotter. Individual histograms to equivalent stimulation were obtained for each of ten to 50 points in a linear or two-dimensional array of adjacent locations within and surrounding the RF on the skin. Intensities of the evoked unit responses in these histograms were calculated either as the number of spikes/stimulus within a user specified response epoch, or as a percent increase in firing rate within that epoch. Plotting this data along a one- or two-dimensional axis then revealed the precise location and "shape" of the RF. Additionally, a statistical test (Student's t) was implemented on the computer to determine whether the firing rate within the response epoch (from 5- to 15- msec latency; 10-20- msec duration) of the histogram was significantly different from the firing rate during control epochs (measured from 300- to 500- msec poststimulus).

Histological reconstruction of the cortical sites sampled during mapping experiments involved injecting fast green dye through the electrode in at least two of the recording sites, killing the animal after the experiment, perfusing it with 10% formaline solution, removing the cortex from the brain, flattening it with a glass slide on a frozen microtome cutting stage, and cutting histological sections (50 μM) tangential to the cortical surface, which were then mounted, dried, and stained with thionine. The characteristic aggregates of granule cells defining the rat SI cortex (see Fig. 1) are visible in such sections and therefore may be drawn in relation to the spots of fast green deposited earlier during the mapping experiments. Since the same features are easily observable in unstained wet sections some brains were simply drawn or photographed immediately after sectioning.

Recording in the awake rat

For unit recording in the awake animal we have exclusively used the chronically implanted, freely moving preparation rather than the restrained or immobilized (curarized) preparation. The advantages of this technique are: (1) the animal experiences no pain or undue distress; (2) it allows observation of motor and behavioral correlates of recorded cells; and (3) it is possible to keep track of the general arousal level of the animal during sensory testing. Detailed descriptions of the materials and methodologies involved in unit recording in the awake rat have been published elsewhere (Chapin et al., '81; Chapin and Woodward, '82a,b). Briefly, several days before experimentation, rats were surgically implanted with a nylon well over a brain, flattening it with a glass slide on a frozen microtome. The advantages of this technique would reveal cutaneous sensory responses which were not found during the subjective testing procedures. "Low-threshold" responses were defined as those responding to touch forces less than 1.0 gm/ mm². "High-threshold" cells responded only to greater forces. In most cases it was not possible to determine whether such high-threshold responses were derived from cutaneous, subcutaneous, or deep fascia receptors. Therefore, all cells which responded to touching the skin at any force level were lumped into the "cutaneous" category. "Joint movement" cells were rather narrowly defined as those which could be activated only by manipulating around specific joints and sharply tapping muscles belly and tendons. By our criteria, if such cells could also be shown (by use of computer histograms) to respond to any cutaneous touch with a probe, they could not be defined as "joint" RFs because of the possibility that the response to joint movement was generated by concomitant skin movement.

RESULTS

Cytoarchitectural divisions within the rat SI

The overall structure of the rat SI cortex can be visualized in the tangential section through layer IV shown in Figure 1A, and schematically reconstructed in Figure 1B. An obvious feature from the tangential view is that the region considered as the SI cortex is not a cytoarchitecturally homogeneous structure but consists instead of a patchwork array of areas containing dense aggregations of layer IV granule cells, surrounded by granule-cell-sparse regions. As was shown by Welker ('71, '76), and in our own mapping studies (see Fig. 3), this discontinuous pattern of granular, or koniocortical, zones contains within itself a map of the rat's cutaneous periphery. There are clear subtypes within this cytoarchitectural subregion, notably including the "granular aggregate" type of cytoarchitecture characteristic of the paw, limb, and mystacial vibrissae areas, and the "barrel-field" type (originally described by Woolsey and Van der Loos, '70) seen in the nose and perioral regions. In the mouse, but not the rat, such barrels also cover the whole whisker representation (Welker and Woolsey, '74). For the purposes of this investigation, however, we will combine these subtypes into the single category of "granular zones (GZs)."

The granule-cell-sparse regions surrounding the GZs can be further subdivided into three major groups: (1) perigranular zones (PGZs)—transitionally dysgranular cortex surrounding the GZs; (2) "dysgranular zone" (DZs)—almost agranular cortical strips lying caudally between the forelimb and face areas of the SI, and extending rostrally between the nose and lower lip areas; and the (3) the "transitional zone" (TZ) between the granular SI paw areas and the rostrally adjacent lateral agranular cortex, which is considered to contain most of primary motor (MI) cortex (Donoghue and Wise, 1983). The TZ may thus be thought of as a special type of perigranular zone in that it also contains a thick, gigantopyramidal layer V typical of motor
Fig. 1. Topography of cytoarchitectonic zones in the rat SI cortex. A. A thionin-stained 75-μM section cut tangentially through layer IV of a flattened cortex. The granular zones (GZs) appear as dark patches surrounded by lighter, dysgranular cortex. Left = rostral; up = lateral. Bar = 1 mm. B. Schematic drawing of the cytoarchitectural zones visible in A. Granular zones (GZs) shown as black areas, some containing center sparse barrels. Perigranular zones (PGZs) defined as stippled area surrounding GZs, except in Transitional zones (tz’s) just rostral to SI. Dysgranular zones (DZs) lie in center of SI. Medial and lateral frontal agranular areas (AGm and AGl) lie rostral to SI. AGl contains most of primary motor (MI) cortex.
cortex. In the rat, the rostral portions of the fore- and hindpaw granular zones themselves overlie a thick layer V which extends even deeper (1,550 µm) than does layer V in the MI cortex (about 1,420 µm).

The exact criteria for differentiation of the GZs, PGZs, TZs, and DZs are somewhat arbitrary in that the cytoarchitectural transitions are gradual in many regions of the SI. In fact, this classification scheme was chosen partly because important neurophysiological differences between them were discovered in the experiments described below.

**Cutaneous RFs in anesthetized animals**

The first phase of this investigation involved a precise mapping of the SI cortex in rats anesthetized with pentobarbital or Halothane. The main purpose was to determine whether a single or multiple representation exists in the rat SI, and to correlate this map with the cytoarchitectural zones defined above.

In order to provide the background information necessary for this mapping, a series of initial studies were devoted to quantitatively defining the properties of cutaneous RFs in the SI cortex. The first problem was to assess the specificity and homogeneity of cutaneous RFs recorded within given vertical microelectrode penetrations through cortex. Such a demonstration of uniformity of RF location is necessary in any mapping experiment since no map can be produced if single units with markedly different RFs coexist within the same vertical column. In fact, it was generally found that neuronal responses to cutaneous stimulation varied in their force threshold, latency, frequency response, excitation-inhibition patterns, and RF size, especially across different cortical layers. For instance, layer V neurons consistently exhibited larger RFs than layer IV neurons.

Despite these differences between RFs of neighboring neurons, we found that the locations of the "centers" of the RFs remained constant throughout vertical penetrations. Figure 2 illustrates the results of an experiment which illustrated this phenomenon. Computer generated poststimulus histograms were used to map the size and spatial location of cutaneous receptive fields (RFs) of different single units in a single vertical penetration through the SI forepaw area of a barbiturate-anesthetized rat. Histograms were generated of the units' responses to probe touch (0.5-gm force; see Methods) of each of 18 points spaced 1.0 mm apart in a line from the tip of the digit to the wrist.

The responses (in spikes/stimulus) of each unit to probe touch (at about 1 Hz; 20–40 repetitions) at each of these points were calculated and graphed as a function of stimulus location (see Fig. 2). The units responded most intensely within a central area of the RF and less intensely as one progressed toward the periphery of the RF. Because of this trailing off, the exact outer boundaries of such RFs were difficult to determine. By our definition, an "RF" is the whole area from which responses can be elicited according to proper statistical tests of reliability.” For example, we have used a one-tailed Student's t-test to define such boundaries—i.e., it was used to determine whether the weak neuronal responses to stimulation near the RF's peripheries were statistically significant (P < .005), or were simply due to random discharge, in which case, they were plotted as 0.0 spikes/stim (Fig. 2).

Figure 2 also shows data comparing the accuracy of determining RFs by subjective means as opposed to the more quantitative techniques shown above. After mapping the

![Fig. 2. Computer determination of cutaneous RFs of single (a-c) and multiple unit cluster (d) in layer IV of SI forepaw area in an anesthetized rat. Evoked unit responses (in spikes/stimulus) were calculated in the period between 7 and 20 msec poststimulus from histograms generated by probe touch (0.5 gm) of each of 17 points on the paw (black-filled circles). Stippled area shows the RF determined by aural monitoring of the unit responses.](image)
RFs of three units (shown in 2a, 2b, and 2c) isolated from 600 μM to 750 μM cortical depth, the trigger threshold was lowered so that about six units were discriminated above the noise level, and the RF was defined again (shown as "Multi," in Fig. 2d). Though this RF appeared somewhat larger, its basic shape was unchanged from a, b, and c. Also shown in Figure 2 is the RF (stippled area) which was determined subjectively by listening to the raw electrode recording at a depth of 750 μm before obtaining the quantitative RFs (a–d). It can be seen that the RFs determined by all these techniques were concentric, though they were of different sizes.

The overall picture that emerged from these experiments, however, was that the exact locations of outside boundaries of such RFs may be of less importance than the shape, location, and intensity near their centers. This view is reinforced by the findings that the total sizes of RFs are not static but are a dependent function of stimulus intensity, frequency, and quality, as well as anesthetic level. By contrast, our data indicate that the location of the RF center is relatively static under all these conditions. Because of this finding, we have chosen to use the RF centers, rather than the whole RFs, for mapping the cutaneous periphery in these experiments.

The cutaneous map in the rat SI

The representation of the cutaneous periphery in the SI was mapped in 37 rats. In each experiment, a total of 25–150 (total = 2,150) microelectrode penetrations were made perpendicularly into cortical layer IV. Penetrations were made at intervals of 50, 100, 200 or 500 μm in two-dimensional arrays over the surface of the cortex. RFs were deter-

![Fig. 3. Composite map of the cutaneous representation in the SI cortex of the anesthetized rat, determined by microelectrode mapping. Abbre-viations, from caudal to rostral body regions: T, trunk; hl, hindlimb; HP, hindpaw; dhp, dorsal hindpaw; dl-5, digits 1–5 of hindpaw; hm, hindlimb muscle; vfl, ventral forelimb; dl, dorsal forelimb; w, wrist whiskers; dlp, dorsal forepaw; p, palm; dl-5, digits 2–5 of forepaw; t, thumb (pollux); UZ, zone unresponsive in anesthetized recordings; A–E, 1–8, rows (from dorsal to ventral) and numbers (from caudal to rostral) of mystacial vibrissae; RV, rostral small vibrissae; N, nose; FBP, frontalobuccal pads; UL, upper lip; LL, lower lip; Lo, lower jaw.]
Fig. 4. Mapping the SI forepaw area. A. Sequence of microelectrode penetrations (spaced at 100 μM intervals into the forepaw area and environs (see Fig. 3 for labeling of map divisions). Left of figure is rostral, top is lateral. B. RFs on dorsal forepaw (above) and palmar surface (below) corresponding to numbers of penetrations shown in A. Drawings on left show RFs recorded in the rostral forepaw representation. C. Histological verification of the positions of electrode tracks. Stars indicate the locations of fast green dye injections (which are too small and the wrong color to be seen in this photograph). Injections were made after first and 80th electrode penetrations. Bar = 1 mm.
were very sensitive to whisker manipulation, but much less so to stimulation of the skin and fur surrounding the whiskers. The more rostral cortical areas representing the perioral regions contained many large RFs which extended into the whisker area and included the skin and fur surrounding the vibrissae (see similar findings of Pidoux et al., '79).

A similar arrangement was seen with regard to the small group of long whiskers emanating from the ventral surface of the rat’s wrist. These were represented by their own granular aggregate, similar to those of the vibrissae. The skin and fur surrounding them were represented much more diffusely in large RFs throughout the forelimb area of the SI.

**Discontinuities in the representation: dysgranular cortex**

The reconstructed map illustrated in Figure 3 features an almost continuous representation of the contralateral body surface. This continuity was marked by the finding that, as one progressed through successive locations of the cortical map, the RFs always overlapped with those seen in preceding and succeeding penetrations. There were several locations within this map, however, where discontinuous portions of the body representation abutted against each other. When such boundaries were crossed the RFs defined in the successive penetrations did not overlap the way they did when mapping across continuously represented zones. Such boundary areas were found only between the hind- and forelimb, the forelimb and face areas, and the lower jaw and face areas. Typically, they featured a cytoarchitectonically dysgranular cortex which separated and delimited the granular cortex (GZs).

Figure 5 illustrates an experiment which demonstrated the sequential changes in RFs across the boundary region between the forepaw and lower jaw representations, a boundary marked by a narrow dysgranular strip delimiting the GZs corresponding to the two body areas. The solid lines in Figure 5 define the locations of the lower jaw (LJ) and forepaw (FP) GZs, while the broken lines define the perigranular strips. In the first series of penetrations (made in 100-μm steps) the centers of the cutaneous RFs shifted from the center of the palm (P1), to the pollux (P4), and then to cover a large portion of the dorsomedial surface of the paw (P6). The very next penetration (P7) encountered exclusively lower jaw RFs, whereas in P6 only forepaw RFs were found. The sharpness of the transition across this boundary was further tested by making oblique penetrations through the cortical convexity such that the granular layers of the forepaw and then the lower jaw area were traversed at an angle tangential to the cortical surface. Neurons recorded in such experiments typically exhibited exclusively forepaw RFs until the boundary was crossed. Then, within 50 μm, neurons with exclusively lower jaw RFs were recorded.

The DZs, unlike the PGZs, did not exhibit reliable cutaneous RFs in anesthetized animals. This was shown in Figure 5, where a second series of penetrations was made more caudally than the first series such that a 200-μm stretch of dysgranular cortex was crossed in the progression from lower jaw to forepaw area. In the three penetrations (P14, P15, and P16) in this series that crossed through this zone, no sensory responsive neurons were found.

A similar pattern was found in other regions of the SI cortex. The vibrissae field, for example, contains discrete aggregates of granular cells, corresponding to small (0.3–
0.5-mm diameter) GZs. These are embedded in a less granular matrix, containing a granule cell density similar to the PGZs surrounding the paw areas. Our recordings in this region showed that highly discrete RFs, often corresponding to just a single vibrissa, can be found in the centers of these granular aggregates, while multiwhisker RFs were recorded in the surrounding matrix of perigranular cortex. If penetrations were made extending more than 300 μm medial from the vibrissae field into the DZs, however, no sensory reponses could be obtained.

Recordings in the fore- and hindlimb areas have yielded similar findings as well. These areas are characterized by long, narrow GZs surrounded by a matrix of perigranular cortex. Relatively discrete cutaneous RFs on the limbs were recorded in the GZs, while large, diffuse RFs were found over much of the rest of the area. Thus, it appears that clear physiological differences can be correlated with cytoarchitectural zones in the rat SI cortex.

Responses to joint movement

In barbiturate-anesthetized animals, neurons responding exclusively to passive joint manipulation were found consistently only in the narrow strip of cortex just rostral to the SI forepaw and hindpaw areas. These zones (see forelimb muscle—"fm", and hindlimb muscle—"hm" in Fig. 3) correspond to the TZ (see Fig. 1A).

Figure 6 illustrates an experiment which demonstrated the transition from cutaneous to joint receptive fields in a sequence of penetrations moving in a rostral direction from the SI hindpaw cutaneous area. Neurons recorded in P1–P6 exhibited exclusively cutaneous RFs on the plantar surface which shifted distally toward the tip of the third digit as more rostral hindpaw regions were penetrated. Neurons in P7 responded mainly to tapping the claw with a probe while the digit itself was held immobile.

Rostral to P7 no cells were found which responded to any form of cutaneous stimulation. Instead, the neurons in P8 and P9 responded phasically to passive extension of the digits when the hindpaw was held to stabilize the ankle joint. While some activity was evoked by flexing digit 3 alone, the strongest responses were obtained when digits 2–5 were flexed simultaneously. The evidence for the notion that these neurons were responding to passive stretch of muscle receptors in the digit extensors was strengthened by the finding that they also discharged when sharp taps were applied to the plantar region of the hindpaw—where the tendons of the flexor digitorum longus and flexor digitorum brevis muscles are situated.

As more rostral cortical areas were penetrated, neurons were recorded which responded to rotation around more proximal joints. Discharges in P10 were obtained by passive flexion of the heel joint, by tapping the calcaneus tendon, and by deep palpation of the triceps surae. Again, this evidence suggests the neurons were responding to stretch of muscle receptors (in this case, sural muscles) and not exclusively to activation of joint receptors.

In barbiturate-anesthetized animals, no clear sensory responses to joint movement could be repeatedly elicited in more rostral locations, nor anywhere else in the SI outside this narrow strip of TZ. However, in recordings in awake animals (and to some extent those lightly anesthetized with Halothane), joint movement RFs were consistently found throughout the lateral agranular (MI) cortex (as well as several areas within SI, described below). Though the somatotopy was somewhat diffuse, such RFs involving more proximal limbs were generally found as one recorded more rostrally in the MI, while more distal RFs were found in the caudal MI. This suggests the representation of distal joints recorded in the TZ may constitute the caudal portion of the "joint-muscle map" of the body in MI cortex.

Somatic sensory properties in awake animals

The second phase of this investigation involved a characterization of somatic sensory properties of single SI units in unanesthetized rats. For humane reasons, and because we wanted to assess motor and behavioral correlates, as well as passive sensory responses, we utilized awake, freely moving, rather than curarized preparations. Such animals, when habituated to human handling, remained quite still during the various manipulations used to determine somatosensory RFs. Several differences were noted between the discharge properties of neurons in these awake rats as compared to similarly located neurons in the anesthetized. Specifically, (1) cutaneous RFs were larger, more complex, and more volatile, (2) joint RFs, movement correlates, and sensorimotor interactions were found, and (3) behavioral modulation of sensory responses was common. Despite the addition of the above properties, the overall map of the SI body representation defined in the anesthetized animals remained essentially unchanged.

Cutaneous RFs in awake animals

While in the anesthetized state cutaneous RFs were mainly found in the GZs cortical areas, in the awake state cutaneous responses could be evoked in nearly every part of the SI. However, as one progressed away from the GZs higher proportions of joint RFs (discussed below) were encountered, and the cutaneous RFs exhibited more "com-
plex" properties. Therefore we will discuss the GZs and DZs separately.

A major question which we attempted to resolve here was whether the map of the cutaneous periphery definable in the anesthetized animal is relevant to the situation in the awake, behaving animal. Specifically, are the RFs characterized under anesthesia predictive of the RFs of the same units in the awake state? To shed light on this question, 231 single units were recorded in the fore- and hindpaw areas of the SI cortex of rats chronically implanted with a microelectrode drive apparatus (see Methods). We were able to test 23 of these neurons under anesthetized conditions as well by first characterizing their properties in the awake situation and then applying Halothane (0.5-1.0% inhalation, n = 19) or pentobarbital (I.P., 40-50 mg/kg B.W., n = 4) anesthesia.

Each cell was subjected to a standard procedure for characterization of RFs and other discharge properties (see Methods). It was clear that, in the awake state, cells in all cortical layers had larger RFs, some even responding in a nonspecific fashion to touching anywhere on the body. However, such wide field responses were extremely volatile and seemingly dependent on the behavioral state of the animal. For example, many neurons, especially in the surragranular layers, would discharge initially even when the experimenter's hand approached the animal. These responses would quickly habituate, but the neurons would still respond to touching anywhere on the body. Often RFs would seem to "travel" from place to place on the skin surface.

After continued handling, such nonspecific responses usually habituated and a rather circumscribed skin area was found, which when lightly touched with a small probe would reliably elicit neuronal responses. Further increasing the stimulus frequency shrunk the RF further down to what might be considered the "RF center," stimulation of which produced the most reliable and intense responses.

Figure 7 illustrates an experiment in which three units (b, c, and d) were recorded within a single vertical penetration into the SI forepaw area (from about 1,000-1,300-μm depth from pial surface). Their RFs were mapped quantitatively by histogramming their responses to probe touch (0.5-gm force, at about 1 Hz) of nine different sites (2 mm apart) within a line stretching from the tip of the phalanx to the wrist. These three neurons exhibited markedly different discharge patterns relating to various motor and behavioral states. Specifically, c fired when the rat actively moved its forelimb, b fired during movement only when the forepaw touched an object, and d responded nonspecifically to a wide variety of different sensory stimuli. Figure 7 shows that their cutaneous RFs on the paw, however, were remarkably similar.

While still recording the last of these cells (b), the animal was given an injection of pentobarbital (50 mg/kg B.W.). After 10 minutes the animal became comatose and the RF was tested again using the same stimulus parameters (a). It can be seen that the anesthesia reduced the intensity of response to stimulation of all the skin sites, and perhaps sharpened the peak of the RF center. However, the overall shape and location remained the same. Further, the location of the RF center of this neuron closely matched those of the other cells in this penetration. Thus, despite the fact that neurons recorded in the awake, behaving animal were

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Fig. 7. Comparison of RFs of a single unit mapped in both awake and anesthetized conditions. Unit responses (in spikes/stimulus; see text) to touch of 2-mm-spaced points on the forepaw (right) are plotted left. RFs of layer V single units b, c, and d determined in a single penetration in an awake animal. Unit b was then retested after I.P. administration of pentobarbital anesthesia, to yield RF (a).
highly variable, their clearest, most reliable properties were those which could be defined in the anesthetized state.

**Joint RFs in awake animals**

While neurons recorded in the GZs exhibited predominantly cutaneous properties regardless of anesthetic state, a combination of joint and cutaneous RFs were found in the DZs and PGZs in awake animals. As in the GZs the sensory properties of neurons in the dysgranular areas were much more volatile in the awake than the anesthetized state, yet in the GZs a precise topographic representation of the cutaneous periphery was maintained as a central component of neuronal firing during waking behavior. Neurons in the PGZs, and especially, DZs, on the other hand, were mainly unresponsive during anesthesia, and, as might be expected, their RFs were also more difficult to characterize in the awake. Nevertheless, large numbers of the neurons recorded in these regions possessed very clear and specific cutaneous or joint RFs. In progressing from the GZs through the PGZs, to the DZs, the joint modalities became more predominant. In the same progression, cutaneous RFs remained common, but grew larger, more volatile and complex, and covered more proximal body parts. Both joint and cutaneous RFs were often found in the same penetration, and represented roughly the same somatotopic area. For example, units responding to rotation around the elbow joint were found near to units with cutaneous RFs on the upper forelimb.

Figure 8 illustrates the results of a careful testing of six neurons within a single vertical penetration into the perigranular forelimb area of the SI in an awake rat. Unit 1 was typical of superficial layer III neurons in this area in that it did not exhibit clearly definable sensory or motor properties. It was mainly responsive to nonspecific behaviorally arousing stimuli such as touching anywhere on the body, loud sounds, presentation of novel objects in the recording chamber, and movement of the experimenter's hand toward the animal. All of these responses tended to habituate after only a few repeated presentations of the stimulus. During active movement these neurons generally increased their firing rate but did not discharge specifically in relation to a particular aspect of the movement.

Units recorded in deep layer III and layer IV in the PGZ tended to exhibit moderately specific cutaneous RFs. The RFs of units 2 and 3 were both centered on the ventral wrist and covered large areas of hairy skin on the forelimb. Like most cutaneous neurons in the rat SI, unit 2 was classified as rapidly adapting. Unit 3, however, responded tonically to maintained touch. Such slowly adapting units comprised about 14% of the units recorded in the DZs, but only about 3% of units in the GZs in the awake animal.

Another phenomenon of cutaneous RFs seen in the awake but not the anesthetized animal was the presence of higher-order complex RF properties. For example, many units in the PGZs, and especially the DZs, exhibited bilateral cutaneous RFs. Other cells responded to cutaneous stimulation if the skin or fur was rubbed in a certain direction, or touched during a certain behavioral or motor situation. Since such contingencies often became quite complex, a full description cannot be attempted here.

Specific responses to joint manipulation were found in all cortical layers but were most common in layers V and VI.
Characterization of such RFs required a very careful systematic testing of responses to several different stimuli. Typically, units in this area classified as having joint RFs responded to rotation around one or several joints, to deep palpation of muscle bellies, and often to sharp tapping of the skin overlying muscle tendons. Obviously, it was very important to determine that such responses were not the result of activation of cutaneous receptors. To guard against this, all such cells were tested for cutaneous sensitivity by touching skin areas on the same limb with the wire-tipped probe and generating histograms. Even if small responses resulted from this procedure, the cells were not classified as having joint RFs.

Units 4 and 6 in Figure 8 are good examples of "joint movement" cells. These did not respond at all to light touch of glabrous or hairy skin, to movement of hairs, or to rubbing objects in different directions on the skin. They responded strongly, however, to manipulations which would be expected to stimulate joint or muscle receptors. Unit 4 discharged a phasic burst of spikes whenever the experimenter rapidly extended the paw around the wrist joint. It then maintained a tonic discharge as long as the paw was held in that extended position. Extending individual digits was somewhat less effective in producing this response. Neither wrist flexion, nor elbow flexion or extension were effective stimuli. This unit was also very sensitive to tapping the ventral surfaces of the digits, palm, and wrist, and to deep palpation of the antebrachial flexors. These responses were distinguishable from cutaneous responses in that when the paw was held still and the skin was touched, the unit did not respond. Unit 6 was similar to unit 4 except that it responded to manipulation around both the wrist as well as the elbow joint.

In some cases, convincing evidence was found indicating a convergence of deep and cutaneous modalities. Unit 5 (in Fig. 8), for example, responded phasically to touching the skin of the palm and the hair of the ventral antebrachium, but also discharged tonically during passive elbow flexion. Since no such tonic firing could be elicited by touching the skin of the paw or limb, or even to stretching the skin of the elbow, this cutaneous responsiveness was not considered capable of causing the elbow flexion response. This, and a small group of similar neurons, were separately classified as "cutaneous + joint."

An additional feature of neurons with joint RFs was that they also discharged strongly during active movement. Most of these discharged during active movements in the opposite direction from which they responded to passive joint manipulation. Many other neurons, especially in the AG1-MI cortex, exhibited little or no responsiveness to passive joint rotation, but discharged strongly during active movement around the same joint. Such units, which we have classified as "active joint," have been identified throughout the AG1-MI and SI cortex, even in the forepaw GZ, where no passive joint responses were found.

Figure 9 and Table 1 summarize the results of experiments involving 82 separate vertical microelectrode penetrations into the forelimb and hindlimb areas of the MI and SI cortices in awake animals. Each penetration involved characterization of RFs of four or more single units. The locations of these penetrations (as determined by follow-up histology) are plotted relative to the map of the SI GZs defined in Figure 1. Penetrations were defined in three categories: (1) those in which >95% of all units with sensory RFs were cutaneous, the remainder being either joint or undefinable; (2) those in which at least 10% of such RFs were joint; and (3) those in which 50% or more were classified as joint. Table 1 illustrates a more detailed classification of the total sample of units recorded in (1) the granular forepaw or hindpaw areas, (2) the forelimb and hindlimb areas, which were so heterogeneous that both granular and PGZs were included, (3) the DZs, and (4) the AG1-MI cortex. The units classified in Figure 9 as "joint" were subdivided into three categories shown in Table 1: "joint," "cutaneous + joint," and "active joint." Examples of these categories have been described in detail in the above section relating to Figure 8. Neurons unresponsive to any manipulation, and those with only nonspecific properties, are lumped in the "other" category. Percentages of the total number of cells with specific RFs (i.e., not including "other") in each cytoarchitectural zone are shown in parentheses. It can be seen (Fig. 9) that in the fore- and hindpaw GZs virtually all units exhibited cutaneous RFs, while more caudal and rostral areas exhibited larger proportions of joint RFs. As such, the different dysgranular areas all appeared to feature a greater variety of properties than the GZs, both in the convergence of different modalities onto different cells in the same area, but also onto the same cells (i.e., cutaneous + joint). These findings may therefore not only indicate a correlation of cortical cytoarchitecture with sensory modality, but also with the degree of sensory integration.

**DISCUSSION**

The evidence obtained in this study leads us to conclude that the rat SI cortex contains but one body representation. To a large extent, this conclusion stems from our somewhat conservative definition of a "representation" as a zone which contains a demonstrably separate, complete, and topographically organized map of a receptor surface. It was not possible here to demonstrate more than one body representation satisfying these criteria. On the other hand, the map of the body in the rat SI may fail to satisfy some criteria for a single representation. Specifically, it was found to contain a heterogeneous array of subzones which varied markedly...
in their cytoarchitecture, somatosensory modality, and also their apparent level of physiological complexity.

In fact, one class of subzones, the GZs, was shown (in agreement with Welker [71,76], Hall and Lindholm [74], and Pidoux [79]) to contain, within themselves, a single complete representation of the cutaneous periphery. This map of skin and hair receptors exhibited a remarkable continuity, with the paw, limb, and face areas linked to each other though a caudal trunk area. Only the forepaw was multiply represented (corroborating a recent observation by Welker et al., '83).

While it was clear that a single complete cutaneous representation existed in the GZs, the other subzones within the rat SI (the PGZs and the DZs) did not contain separate representations. Instead they appeared to replicate the same representation, but at a more integrative and polymodal level. For example, the PGZs surrounding the GZs contained larger RFs which covered the same skin areas, thus fitting more diffusely into the same body map. These subzones (along with the DZs) also contained a representation of muscles and/or joints, which partially overlapped the cutaneous representation. These fit into the same body map by virtue of the fact that the joint RFs and cutaneous RFs of nearby cells always referred to closely adjacent body areas. In a similar fashion, the more physiologically complex (and anesthesia sensitive) RFs characteristic of the DZs usually contained a major component which fit (though diffusely) into the somatotopically appropriate part of the map. Thus, the whole body representation might be thought of as extending across cytoarchitectonic boundaries, including overlapping subrepresentations of different somatosensory submodalities, and also including cortical zones which operate at more of an "associational" level of processing than the primary receiving zones.

Comparison with other species

The basic organization of GZs in the rat appears to be quite similar to the squirrel (Sur et al., '78). The overall orientation of the body is similar (i.e., with the nose and mouth rostralateral, and the tail, trunk, and hindlimb caudomedial). The forepaw regions in both rat and squirrel are represented twice. Finally, the SI cortices of both species contain a central dysgranular zone (termed "unresponsive zone" by Sur et al., '78) between the forelimb and face representation.

Similar comparisons might be made with the map of the SI cortex in the cat, which was defined first by Mountcastle ('57), and more recently by Dykes and Gabor ('81). These studies showed a similar displacement of cutaneous submodalities toward the rostral SI, and "deep" submodalities toward the caudal SI. Furthermore, Dykes and Gabor showed in the cat a phenomenon we observed in the rat, i.e., a tendency for joint movement RFs to be found in the deep layers of cortex, while cutaneous RFs were more common in layer IV.

There also appear to be some similarities between the rat and monkey SI. Most noticeably, the overall orientation of the cutaneous map in the rat SI is similar to that in the primate area 3b (i.e., with the head representation lateral; the tail and rear extremities medial; the trunk caudal; and the distal extremities and perioral regions rostral). This fact has led Kaas ('83) to speculate that area 3b in primates is the exclusive homologue of the SI cortex in rodents and squirrels.

The findings of the present study suggest the GZs themselves in the rat SI might comprise a homolog of the monkey area 3b. This is supported by the following findings: (1) both the GZs in the rat SI and the monkey area 3b comprise the most granular parts of their respective SI cortices. (2) Both subserve mainly cutaneous sensory modalities, while the less granular parts of SI subserve more "deep" modalities (Powell and Mountcastle, '59). (3) In general, both are located more rostrally within the SI cortex than the dysgranular cortical zones. (This effect is, of course, much more pronounced in the monkey than the rat, partly because the rat's vibrissae zones is greatly expanded in a caudal direction.)

Several differences between the GZs in the rat and the monkey area 3b must, however, be noted: (1) the GZs representing the paws in the rat SI may partially overlap with the rostrally adjacent motor cortex (Donoghue and Wise, '82), and as such are underlain by a thin gigantopyramidal cell layer, while the primate area 3b is not. (2) The GZs in the rat SI appear as a discontinuous array of granular islands dispersed within a matrix of less granular cortex, while in the monkey these boundaries demarcate separate body representations. It is conceivable that all these differences between the rat and monkey SI cortices may be attributable to a relatively greater degree of functional overlap in the cerebral cortices of primitive mammals. The process of primate evolution may have involved a coalescence of functionally similar zones and a separation of functionally different zones. Formation of the continuous koniocortical strip in area 3b could have resulted from a rostral merging of GZs. The dysgranular cortical areas (formerly associated with GZs, but now merging caudally) might have also developed separate, though more diffuse, body representations. Further comparative studies are needed to test this notion.

Is there an area 3a in the rat SI?

In the present experiments we have consistently found that neurons located in the TZ (the narrow strip of cortex just rostral to the GZ forepaw and hindpaw areas) responded predominantly to joint movement. The fact that these neurons also responded to deep muscle palpation and tendon tap is consistent with the notion that this region receives muscle receptor input. A narrow band of cortex just rostral to area 3b activated by muscle receptor inputs has long been known in cats and monkeys (Rosen, '69; Dykes et al., '80; Rasmussen et al., '79; Hassler and Mumby-Clement, '64; for review see Jones and Porter, '80). Recently, Johnson et al. ('82) have indicated that a band of cortex just rostral to he cutaneous representation of the forepaw apparently was activated by muscle receptors in the raccoon. The characteristics of the TZ in the rat appear
to be similar to some of the anatomical and physiological features of area 3a in these other species. However, a final conclusion as to the existence of this homology awaits further detailed connectional studies.

**Functional role of dysgranular zones**

Overall, we found a greater "complexity" of sensory properties in the PGZs and the DZs. This was reflected in a convergence of joint movement and cutaneous sensory modalities, and also in the fact that cutaneous RFs were larger, were sometimes bilateral, often were directionally selective, and/or exhibited behavioral modulation of their sensory response. Similar observations have been made in the more caudal regions of the SI cortex in monkeys (Hyvarinen and Poranen, '78a,b). In rodents, the complex receptive properties found in the DZs may be partially explained by the fact that they are known to receive rich contralateral and ipsilateral corticocortical connections (Wise and Jones, '76; Akers and Killackey, '78; Lin et al., '80; Donoghue and Parham, '83; Chapin and Woodward, '82c; Killackey, '83). Extensive corticocortical connections of the DZs (called the "unresponsive zone") have also been described in the grey squirrel (Gould, '81; Gould and Kaas, '81). A similar preponderance of corticocortical connections with the caudal SI cortex (areas 1 and 2) has been reported in the primate (Jones et al., '78). The dysgranular zones in rats (and possibly in monkeys) might therefore be considered as relatively "associational" cortices existing with the primary receiving zones of the SI.

**Classification of somatosensory submodalities**

There has always been a major problem in differentiation between the various somatosensory submodalities when recording neurons at the cortical level. It is particularly difficult to differentiate between high-threshold cutaneous receptors and deep receptors not activated by joint movement. For this reason, we have not attempted to separately subclassify "deep-tap" responses, and have instead lumped these into the cutaneous category. It is perhaps for this reason that the percentage of "joint" cells defined in this study appears to be consistently lower than the percentages of "deep" cells described across the SI cortex in other species (see Dykes and Gabor, '81; Powell and Mountcastle, 59).

**Legitimacy of mapping methods: use of anesthetics**

A final comment must be made concerning the methods utilized in mapping studies in general, and here in particular. It is, of course, axiomatic that the ability to determine whether sensory representations are single or multiple depends on the discreteness and homogeneity of the RFs recorded within each microelectrode penetration. We found in our quantitative studies of RF properties in both awake and anesthetized animals that an emphasis on the location on the skin of the centers of the RFs allowed a fine-grain mapping of the cutaneous representation. Specifically, within given cortical penetrations in anesthetized animals, RF centers remained quite constant, even though great variability was found in the RFs' size, force threshold to response, frequency response, signal-to-noise ratio, and excitatory-inhibitory response pattern. This rule held true even in layer V, where RFs were much larger, and in awake animals, where RFs were large and volatile (see Chapin et al., '81). Our data therefore agree to some extent with that of McKenna et al. ('81, '82) and Duncan et al. ('82), who reported that the ability to map the cutaneous cortex diminished in awake cats, and monkeys because of the large RF size. However, the relative invariance of the locations of the RF centers through different anesthetic states suggests that maps obtained in the anesthetized animal are quite valid. As such, the anesthetic state may be thought of as a tool for limiting the repertoire of physiological responses of cortical neurons so that the most anesthesia-resistant properties can be most readily identified. Such maps should not lead to the false conclusion, however, that they define the only functions carried out in a given cortical region, or that the sensory properties are reflected in exactly the same physiological manner as in the awake.

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**LITERATURE CITED**


RAT SI