Projections to the Cat Cerebral Cortex from Fore- and Hind Limb Group I Muscle Afferents

AKADEMISK AVHANDLING

SOM MED TILLSTÄND AV MEDICINSKA FAKULTETEN VID UNIVERSITETET I UMEÅ
FÖR VINNANDE AV MEDICINE DOKTORSGRAD
OFFENTLIGEN KOMMER ATT FÖRSVARAS
I SAL A, UNIVERSITETSBYGGNAD LU-O,
FREDAGEN DEN 14 APRIL 1972 KL. 09.00

av
HERBERT SILFVENIUS
med, lic.

Centraltryckeriet, Umeå - 1972
Projections to the Cat Cerebral Cortex from Fore- and Hind Limb Group I Muscle Afferents

by

HERBERT SILFVENIUS

UMEÅ 1972
TO MY FAMILY

Col. 2: 3
VI. DISCUSSION OF THE GROUP I HIND LIMB PROJECTION TO THE CEREBRAL CORTEX .......................... 29
   A. The group I hind limb cerebral path and the dorsal spino-cerebellar tract ........................................ 29
   B. Group II excitation of the group I hind limb cerebral path ........................................................................ 31
   C. Cutaneous afferents converging on the group I hind limb cerebral path .................................................... 32
   D. Contributions from Pacinian and low threshold joint afferents ................................................................. 33
   E. Do Iβ hind limb afferents project to the cerebral cortex? ........................................................................... 34
   F. Functional considerations ............................................................................................................................ 36

VII. GENERAL SUMMARY .......................................................... 39

VIII. ACKNOWLEDGEMENTS ......................................................... 40

IX. REFERENCES ........................................................................ 41
This thesis is based on the following articles:


I. INTRODUCTION

Projection to the cerebral cortex from group I muscle afferents in the contralateral forelimb nerves of the cat was first described by Amassian and Berlin (1958). This projection, located in the region of the postcruciate dimple, Pcd, has been the subject of many studies (Oscarsson and Rosén 1963, Oscarsson, Rosén and Sulg 1966, Swett and Bourassa 1967a, Grampp and Oscarsson 1968). Other investigations have clarified the properties of group I neurones in the ascending path at the main cuneate and the thalamic levels (Andersson, Landgren and Wolsk 1966, Rosén 1969a, b). An increasing spatial integration of information as the path ascends in the nervous system is characteristic for the group I forelimb projection. Another feature of the path is its connexions with cutaneous and group II muscle afferents. The excitation from skin afferents is delayed, suggesting at least one additional synapse in the cutaneous path (Rosén 1970). It has also been suggested that the main part of the cortical group I Pcd cells monosynaptically activated by thalamocortical axons are inhibitory neurones. These neurones are envisaged to participate in a cortical feedback system (Oscarsson et al. 1966).

Forelimb group I afferents do, however, project also to other areas in the cerebral cortex than to Pcd. In addition, it has recently been demonstrated that also volleys in hind limb group I afferents evoke potentials in the cerebral cortex of the cat (Landgren, Silfvenius and Wolsk 1967, Silfvenius 1968, Landgren and Silfvenius 1969).

In this thesis, focus will be centered on the properties of cortical group I neurones in the forelimb projection to the anterior suprasylvian region and on the organization of the ascending hind limb group I projection to the postsigmoid gyrus of the cerebral cortex of the cat.
II. METHODOLOGICAL CONSIDERATIONS

A. ANESTHESIA

Chloralose anesthesia has been used in the present investigations. This anesthetic is assumed to depress inhibitory control (for ref. cf. Denavit 1963). Cortical afferent projection patterns in chloralose anesthesia may therefore differ from those obtained in deep barbiturate anesthesia used in other studies on the forelimb group I projection to the cerebral cortex. Barbiturates are known to exert a general depressant action. Neither form of anesthesia, can, however, be maintained to be more "physiological" than the other. It seems therefore reasonable to claim that the cortical potentials evoked in chloralose anesthesia reveal the available pathways but do not, on the other hand, give exact information about the "normal" functional properties of such pathways.

B. CORTICAL PROJECTION FIELDS

A cortical projection field is here defined as a region where activated afferents evoke potentials after shortest possible delay. The latencies of the potentials equal the conduction time in the fastest paths for the afferent volleys to the cerebral cortex. In cortical projection fields, surface recording yields initially positive focal potentials which in the underlying depth reverse to initially negative ones. A cortical projection field includes focal potentials with amplitudes 20 % or more of maximum.

C. ELECTRICAL STIMULATION OF PERIPHERAL NERVES

Electrical stimulation of peripheral nerves has been used to activate afferent fibres in the present studies. This method has the advantage of exciting synchronously afferent fibres and an accurate timing of evoked potentials is thus achieved at consecutive levels of the ascending path. The problem involved when using electrical stimulation is, however, how to discriminate between afferents from different types of receptors. Many investigations have been carried out in order to solve this problem. They have been successful to a certain extent. The limitations are of significance for the interpretation of the present results.

1. Muscle afferents. It is well known that group I afferents are large fibres conducting at velocities between 72 and 120 m/sec. Fibres from muscle spindle primary endings and those from Golgi tendon organs
contribute to the group I afferents. Group II afferents, conducting at velocities between 24 and 72 m/sec, are considered to supply muscle spindles with secondary endings (Hunt 1954). It should be observed that in the following text the terms group Ia, Ib and II muscle afferents are not necessarily synonymous with primary spindle, tendon organ and secondary spindle afferents. The former terms refer to the thresholds and conduction velocities of the components of the compound action potentials evoked by electrical stimulation of afferent fibres. The latter terms again denote the functional properties of afferents tested with adequate activation of their receptors. The degree of correspondence between these terms will be discussed.

**Group I afferents.** Electrical stimulation of muscle nerves at maximal group I strength may reveal a double peaked compound action potential recorded from spinal dorsal roots. The group I volley evoked by stimulation of thigh muscle nerves was analyzed by Bradley and Eccles (1953) who observed the low threshold fast conducting fibres in the first component of the group I spike, Ia afferents, to be responsible for the monosynaptic excitation and reciprocal inhibition of motoneurones. The slower conducting axons of the second component, Ib afferents, exerted no such effects. The Ia afferents were electrically excitable at threshold intensity (T), the Ib component being recruited at strengths 1.3 to 1.9 T for the Ia fibres.

Exact knowledge of how afferents from primary spindle endings and from Golgi tendon organs are distributed in the two components of the group I compound action potential of nerves from the quadriceps and semitendinosus muscles was offered by Laporte and Bessou (1957). Their studies on electrical thresholds and conduction velocities of axons defined by natural stimulation of their receptors revealed that the fast Ia component of the group I volley almost exclusively (95%) consisted of axons from primary spindle endings, the remaining ones originating from tendon organs. The slower group Ib component did, however, contain fibres from spindle primaries (27%). Maximal group Ia stimulation of these nerves will therefore leave one third of their primary spindle afferents unactivated. The findings of Laporte and Bessou thus essentially agreed with the interpretation of Bradley and Eccles. The last mentioned authors observed, however, that hip and leg muscle nerves lack the subdivision of the group I volley, a finding which may restrict the selectivity of the electrical stimulation method.

Hunt (1954) failed to find a clearcut bimodal velocity distribution for afferents from primary spindle endings and from tendon organs in the nerves to the medial gastrocnemius-soleus muscles. Sumner (1961) reinvestigated group I afferents of the medial gastrocnemius nerve, determining
their conduction velocities, thresholds to electrical stimulation and response to stretch and contraction of the muscle. His results were in accord with those of Hunt. Despite a slight preponderance of fibres from spindle primaries among the fastest conducting afferents, a functional separation of these afferents from those of the tendon organs on the basis of conduction velocity seemed less likely. A greater difference was found in the thresholds of the two fibre types. For the main part of the primary spindle afferents the threshold was around 1.2—1.3 T, whereas the main part of the tendon organ afferents had a threshold of 1.4—1.5 T. Some tendon organ afferents were, however, activated electrically already at threshold strength for primary spindle afferents. In the medial gastrocnemius nerve a large number of fibres from spindle primaries are thus represented among axons of lowest electrical threshold, the fibres from tendon organs predominating in the higher threshold portion. In this nerve electrical discrimination of the Ia and Ib component of the group I volley is also less distinct than in nerves from the quadriceps and semitendinosus muscles.

A study of Coppin, Jack and McIntyre (1969) on semitendinosus afferents indicated that an electrical intensity evoking 30 % of the maximum amplitude group I volley would probably activate primary spindle afferents only. Recently Jack and MacLennan (1971) presented some figures that show to which extent afferents from tendon organs of different hind limb nerves were excited if a stimulus strength was chosen which activated 50 % of the investigated sample of primary spindle afferents, namely, 0 % in the semitendinosus-, 3 % in the soleus- and up to 15 % in the medial gastrocnemius nerves.

In some leg muscle nerves an electrical differentiation between the primary spindle and tendon organ afferents is impossible. Jack and MacLennan observed that with a strength exciting 50 % of the primary spindle afferents of the peroneus longus nerve, more than 40 % of its tendon organ afferents were also activated.

Forelimb muscle nerves have not been studied with corresponding methods. Many of them lack subdivisions of their group I volleys (Rosén 1970).

Electrical stimulation of muscle nerves with group I strength may activate other fibres in addition to the primary spindle and tendon organ afferents. Large fibres from other sensory endings are, however, few in number. Their contributions to the evoked cortical potentials cannot be neglected but they should not be overemphasized. Barker (1962) described paciniform corpuscles in muscle tissue. Since the largest Pacinian afferents conduct around 90 m/sec, they are presumably activated by group I stimulation (Hunt and McIntyre 1960 a, Silfvenius 1970 a). Possible cortical effects from such afferents cannot be excluded on stimulation of
group I muscle afferents, as activation of one single Pacinian receptor suffices to evoke a cortical response (McIntyre, Holman and Veale 1967). Morphologically unidentified, rapidly adapting tap receptors have afferents conducting at velocities up to above 90 m/sec (Hunt and McIntyre 1960 a, Silfvenius 1970 a). These two types of units together with large afferents from Golgi-, Ruffini- and paciniform joint receptors, which may follow muscle nerves (Gardner 1944) could thus be activated by group I stimulus intensity (Skoglund 1956, Andersen et al. 1967, Burgess and Clark 1969 a). Joint afferents seem to travel also in forelimb muscle nerves (Oscarsson and Rosén 1963).

**Group II afferents.** Hunt (1954) reported that in the nerve from the medial gastrocnemius muscle the group II fibres emerged almost exclusively from spindle secondaries. Boyd and Davey (1968) concluded that this applies also to the soleus, semitendinosus, tenuissimus and flexor digitorum longus muscles. Using a normalized value (72.8 m/sec) of the maximum conduction velocity for soleus muscle spindle afferents as the upper limit for the velocity of group II spindle afferents Coppin, Jack and MacLennan (1970) showed that such afferents had electrical thresholds between 1.6 and 8.9 T. This threshold range fits well with earlier data of Eccles and Lundberg (1959) who determined the electrical thresholds of muscle afferents conducting in the velocity range of secondary muscle spindle afferents. A differentiation between central actions evoked by group I and group II afferent fibres was demonstrated by Eccles, Eccles and Lundberg (1957). Of importance in this context was their observation that group II afferents may contribute to central actions already at slightly submaximal group I stimulation intensity.

The group II afferents do, however, not emerge only from secondary spindle endings in muscle. Barker, Ip and Adal (1962) reported 35 % of the endings in the soleus muscle with fibres in the group II category to be morphologically unallocated. Uddenberg (1968 b) found group II forelimb afferents that came from morphologically undefined receptors located in joint regions and presumably also from endings in the periosteum. These afferents may have emerged from tension and tap receptors (Silfvenius 1970 a). Pacinian and joint receptors may also have axons in the group II category.

2. **Cutaneous afferents.** Cutaneous afferents are least suitable for electrical discrimination as they contain afferents from a diversity of low threshold mechanoreceptors. In the hairy skin of the cat the following mechanoreceptors with large afferents (such conducting at velocities \( \geq 70 \) m/sec) have been identified: slowly adapting Type I and Type II endings, rapidly
adapting guard hair, tylotrich hair, field and tap receptors and Pacinian corpuscles (Hunt and McIntyre 1960 b, Chambers and Iggo 1967, Brown and Iggo 1967, Burgess, Petit and Warren 1968). In the pads of the cat both rapidly and slowly adapting units with large axons have been described (Armett and Hunsperger 1961, Jänig, Schmidt and Zimmerman 1968). Afferents from "claw sensitive" units in tissue adjacent to claws (Gordon and Jukes 1964 a, Horrobin 1966) may conduct up to 90 m/sec and have electrical thresholds between 1.1 and 1.9 T (Uddenberg 1968 a).

Low threshold electrical stimulation of skin nerves, low threshold afferents here arbitrarily defined as those activated at or below 1.5 T, will therefore activate several types of afferents. Some selectivity may, however, be present on electrical stimulation of afferents in the cat as in the rabbit, since it has been shown that in the latter animal Type I endings, with afferents in the sural nerve, are exclusively activated when the stimulus is \( \leq 1.3 \) T (Brown and Hayden 1971).

3. Joint afferents. To the author's knowledge there are no studies on the electrical thresholds of functionally defined joint afferents. Studies on calibre spectra of joint nerves have, however, been performed and show a wide range of axon diameters, the largest fibres being 18 \( \mu \text{m} \) in diameter (Nisimoto 1939, Sasaoka 1939, Skoglund 1956). The joint afferents supply Golgi endings, mainly located in joint ligaments (Andrew 1954, Skoglund 1956), Ruffini endings in joint capsule (Gardner 1944, Skoglund 1956) and a few paciniform corpuscles in and around joint capsule (Skoglund 1956). The Golgi afferents are the largest, but they are relatively few. The Ruffini axons are numerous but somewhat thinner and the afferents from paciniform corpuscles may be as large as those from Golgi endings. Physiological studies with recording of afferent activity during joint movements have shown the Golgi and Ruffini endings to be slowly adapting and the paciniform corpuscles to be rapidly adapting units (Body 1954, Skoglund 1956). Physiological identification of endings with characteristics of muscle spindle primaries and of phasic joint receptors other than the paciniform corpuscles, have also been described in joint nerves (Burgess and Clark 1969 a).

Electrical stimulation of joint nerves usually gives a triple peaked compound action potential (Andersen et al. 1967). Low intensity stimulation not exceeding 1.3 T will presumably activate mainly Golgi and paciniform afferents, both relatively few in number and presumably corresponding to the small first component of the compound action potential. The majority of afferents in the large second component of the neurograms, are, with all likelyhood, Ruffini afferents, activated at
strengths between 1.4 and 2.0 T (F. Clark, S. Landgren and H. Silfvenius, unpublished observations). Low threshold joint afferents are here defined as those excited at \( \leq 2 \) T.

4. Concluding remarks. In spite of certain limitations, graded electrical stimulation has proved to be a valuable tool in defining, as a first approximation, central actions evoked by various types of afferents. Conclusive evidence for such actions can be gained from complementary studies with adequate activation of the receptors from which the electrically stimulated afferents emerge.

D. ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASSS</td>
<td>anterior suprasylvian sulcus</td>
</tr>
<tr>
<td>DC</td>
<td>spinal dorsal column</td>
</tr>
<tr>
<td>DLF</td>
<td>spinal dorsolateral column</td>
</tr>
<tr>
<td>DRP</td>
<td>dorsal root potential</td>
</tr>
<tr>
<td>DSCT</td>
<td>dorsal spinocerebellar tract</td>
</tr>
<tr>
<td>EPSP</td>
<td>excitatory postsynaptic potential</td>
</tr>
<tr>
<td>FRA</td>
<td>flexion reflex afferents</td>
</tr>
<tr>
<td>IPSP</td>
<td>inhibitory postsynaptic potential</td>
</tr>
<tr>
<td>Pcd</td>
<td>postcruciate dimple</td>
</tr>
<tr>
<td>SCLT</td>
<td>spinocervicolemniscal tract</td>
</tr>
<tr>
<td>SCT</td>
<td>spinal part of SCLT</td>
</tr>
<tr>
<td>VPL</td>
<td>nucleus ventralis posterior lateralis thalami</td>
</tr>
<tr>
<td>VPL(_l)</td>
<td>lateral part of VPL</td>
</tr>
<tr>
<td>VL</td>
<td>nucleus ventralis lateralis thalami</td>
</tr>
<tr>
<td>VSCT</td>
<td>ventral spinocerebellar tract</td>
</tr>
</tbody>
</table>

III. PROJECTIONS TO THE CEREBRAL CORTEX FROM GROUP I FORELIMB AFFERENTS

A. CORTICAL GROUP I PROJECTION FIELDS

The ascending forelimb group I path to the postcruciate dimple region has been reviewed by Rosén (1970). Group I forelimb afferents project also to the lower bank of the anterior suprasylvian sulcus, ASSS, to the rostral bank of the lateral ansate sulcus and to the lateral sigmoid gyrus (Landgren et al. 1967, Silfvenius 1968). The group I projection to the ASSS region has recently been subjected to a unitary analysis (Silfvenius 1972).
Fig. 1  Diagram of projections to the cerebral cortex from fore- and hind limb group I muscle afferents.

The brain diagram of the medial surface is shown to the left, that of the dorsal to the right.

**Forelimb projections** (black areas). The separate projections to the Pcd and to the lateral sigmoid gyrus are shown according to Silfvenius (1968). The projections to the rostral cortical bank of the lateral ansate sulcus and to the lower bank of ASSS are hidden in the sulci.

**Hind limb projections** (encircled areas). These are shown to illustrate marginal overlap between the Pcd and the dorsal group I hind limb locus. The relations of the group I projections to the cytoarchitecture of the cortex (the different areas delimited by thin lines) are shown according to Hassler and Muhs-Clement (1964).

S.CRU = sulcus cruciatus, S.COR. = s. coronalis, S.ANS = s. ansatus, ASSS = anterior suprasylvian sulcus, Pcd = postcruciate dimple.

Forelimb group I afferents thus project to four different cortical regions, diagrammatically illustrated in Fig. 1 (black areas). This figure also shows the locations of these projections in relation to the cytoarchitectonically defined cortical zones, numbered in the diagram (Hassler and Muhs-Clement 1964). Group I forelimb afferents thus project to sensory cortex, area 2 (ASSS and lateral ansate regions), to the transitional zone between sensory and motor cortices, area 3a (the Pcd projection) and to the motor cortex proper, area 4γ (the projection to the lateral sigmoid gyrus). The preliminary report on the projection to area 4γ described this locus as "rostral to and separate from the Pcd area" (Silfvenius 1968). Unpublished observations confirm this statement. The identity of this projection as a separate area has, however, been questioned. Referring to observations made on cats in deep barbiturate anesthesia, it has been claimed that the projection to the lateral sigmoid gyrus in the chloralose anesthetized cat presumably is an extension of the group I projection to the Pcd (Rosén 1970). Fig. 2 shows that the two projection areas in the pericruciate cortex are separated by an intermediate zone where no or very low amplitude surface positive group I focal potentials are recorded (H. Silfvenius, unpublished observations). This seems to leave no doubt about a separate projection to area 4γ. It is, however, not conclusively settled whether the group I responses in the lateral sigmoid gyrus are evoked by thalamocortical fibres or by an "indirect" path. The latencies were slightly longer than those of the Pcd locus, although also equally short latencies were
Fig. 2 Distribution of forelimb group I focal potentials in the pericruciate cerebral cortex.

Electrical stimulation of the contralateral DDR nerve (DDR = a deep portion of DR except the nerve to the extensor digitorum communis muscle) at 1.5 T evokes potentials in two areas. One projection field is located in the Pcd region, the other separate from that in the lateral sigmoid gyrus. The locations of the recording sites are indicated by the stimulus artifacts, except in the precruciate area, where it is marked with a dot. Pcd and lateral sigmoid projections are encircled by lines which delimit the distribution of potentials with amplitudes 50% or more of maximum. The afferent volley, recorded from the cervical spinal cord is shown below the brain diagram. Timer: 5 msec for cortical potentials, 1 msec for afferent volley. Voltage bar: 200 μV for cortical potentials. Positivity of brain potentials downward. Vertical scale in mm. S.cr. = sulcus cruciatus, S.ans. = s. ansatus, ASSS = anterior suprasylvian sulcus, Pcd = postcruciate dimple.

observed. Further studies may clarify if the group I responses in the lateral sigmoid gyrus are relayed in an extra synapse, and if this synapse is located in area 4γ or elsewhere in the group I projection.

B. SINGLE GROUP I CELLS IN THE ANTERIOR SUPRASYLVIAN REGION

Group I activated cells in the lower bank of ASSS were found at all depths from about 500 μ down, below the hidden cortical surface of this group I
locus. No significant differences in depth location were observed between cells excited at short and long latency. The few group I inhibited neurones encountered were located somewhat deeper, approximately from 1000 μ down. Cells uninfluenced by group I afferents were intermingled with the group I activated cells (Silfvenius 1972). The group I influenced cells of the ASSS group I locus thus have a similar depth distribution as the group I cells of Pcd (Oscarsson et al. 1966, Grampp and Oscarsson 1968). The wide depth distribution of group I excited cells in the ASSS locus seems to support recent anatomical observations that both pyramidal and stellate cells receive specific thalamic afferents (Marty and Fuentes 1968, Jones and Powell 1970, Garey 1970).

1. Group I excitation. Volleys in forelimb group I afferents depolarized two thirds of the cortical neurones in the ASSS region strongly enough to make them discharge action potentials. Often the discharge was repetitive already at volley threshold strength. The subliminal excitation appeared either as rather simple or more complex EPSPs, both types being composed of a few or several unitary EPSPs. The thresholds of the subliminal, as well as those of the propagated group I excitation were generally well below 1.5 T. This strongly suggests that these cells were activated by primary spindle afferents. The interpretation is also supported by the finding that the amplitude maxima of group I-EPSPs were reached at very low stimulus intensities. The mean of the stimulus intensities evoking maximal group I-EPSPs was 1.4 T and occasionally maximal responses were obtained just above volley threshold strength. In about one third of the cells the latencies of the group I excitation suggested monosynaptic linkages to thalamocortical axons. Such cells would thus be fourth order neurones in the group I path to the ASSS locus.

2. Spatial group I excitatory convergence. Typical for the ASSS group I cells was that the majority of them received excitation from a restricted peripheral region. Convergence from two muscle nerves was seen in 14 % and from three nerves in less than one tenth of the intracellularly studied cells. Of interest was the finding that group I hind limb afferents co-excited two cells. This indicates a high degree of spatial integration in certain cortical cells.

3. Excitation from other afferents. Group II afferents co-activated a considerable number of the group I excited cells in the ASSS locus, evoking both EPSPs and action potentials. These afferents thus generally enhanced the excitation initiated by group I afferents. The latencies of the group II effects were at times short enough to suggest monosynaptic linkages
with thalamic relay cells. The group II co-activation was spatially linked both to the nerve supplying the group I excitation and/or to other nerves. The prominent group II co-activation of group I cells in the ASSS region may imply that information from secondary spindle endings in muscle is functionally significant for this cortical group I locus. This contrasts with the observations made on group I Pcd cells indicating that group II afferents were relatively ineffective in producing synaptic potentials (Oscarsson et al. 1966).

Low threshold joint afferents were not connected to group I cells of the ASSS locus. High threshold joint fibres did, however, influence part of the cell sample.

A striking feature of the group I cells in the ASSS locus was their connexions to low threshold cutaneous afferents. Thus every group I cell was co-excited by forelimb skin afferents. The latency pattern of the group I and cutaneous co-activation seemed to justify a classification of the short latency cells into three groups. Primary cortical group I cells had latencies which suggested monosynaptic group I-, and di- or polysynaptic cutaneous linkage from thalamic relay cells. Primary cortical mixed cells were presumably monosynaptically activated by thalamocortical group I and cutaneous axons. Primary cortical cutaneous cells had latencies suggesting a monosynaptic linkage from thalamic cutaneous axons and di- or polysynaptic linkage from corresponding group I fibres. Monosynaptic activation by thalamocortical cutaneous afferents of cortical group I cells was not observed in the Pcd locus (Oscarsson et al. 1966).

4. Postsynaptic inhibition. Inhibitory postsynaptic group I potentials were observed in a few cells of the ASSS locus. The group I afferents evoked IPSPs with latencies at least 1 msec longer than those of the shortest EPSPs. Some IPSPs were summating with EPSPs. The group I inhibitory spatial convergence pattern in the ASSS cells was simple, the cells generally receiving inhibitory input from only one muscle nerve.

Cutaneous and group II afferents converged with inhibition on the group I inhibited cells. Very few inhibitory potentials in group I activated cells evoked by cutaneous and group II afferents were observed.

C. CELLS UNINFLUENCED BY GROUP I AFFERENTS

Cells of the ASSS locus not influenced by forelimb group I afferents were either totally unresponsive to the peripheral stimuli used, or activated by forelimb skin and/or group II muscle afferents in combination with input from other afferents. Inhibitory potentials were at times observed (Silfvenius 1972).
IV. DISCUSSION OF THE UNITARY ANALYSIS OF THE GROUP I LOCUS OF THE ANTERIOR SUPRASYLVIAN REGION

A. COMPARISONS WITH OTHER GROUP I NEURONES

Common for cortical group I cells of the ASSS and Pcd regions are their efficient synaptic linkages to group I fibres and their short latencies. ASSS group I cells with latencies about 7 msec or less are presumably activated monosynaptically by thalamic group I relay cells as is also suggested for the corresponding short latency Pcd cells (Oscarsson et al. 1966).

The ASSS group I cells now studied differed, however, from those of Pcd in several respects. The latency of the group I excitation in a number of ASSS cells suggested a disynaptic activation by thalamocortical axons. In the Pcd sample such cells were indeed exceptional. This discrepancy may be related to experimental differences in the two studies, as the present recordings were not chosen from the "center" of the ASSS group I locus, where one would expect to get mainly short latency potentials.

ASSS cells had a meagre group I excitatory convergence pattern resembling thalamic group I cells more than cortical Pcd cells. A large number of ASSS cells were, in fact, activated by group I afferents of one forelimb nerve only (Oscarsson et al. 1966, Rosén 1969 b, Silfvenius 1972). Some group I cells of the ASSS locus were, however, similar to those of Pcd in having quite extensive group I excitatory convergence.

The group I excited cells of ASSS further differed from the corresponding ones in Pcd in receiving a considerable amount of co-activation from group II afferents.

A striking difference between the group I cells of the two cortical areas was that all the ASSS cells were co-excited by cutaneous afferents. In many of them this excitation was presumably evoked monosynaptically by thalamocortical axons. In Pcd group I cells, as well as in thalamic and main cuneate group I cells, at least disynaptic excitation from cutaneous fibres has been observed (Oscarsson et al. 1966, Swett and Bourassa 1967 a, Rosén 1969 a, b). Some ASSS group I cells had, however, similar afferent connexions as the Pcd cells in this respect.

The observed differences in ASSS and Pcd group I cells provoke the question: are group I cells of the two cortical loci linked to functionally different forelimb group I paths? Rosén (1970) recently gave a detailed account of the forelimb group I path to Pcd. His investigations of the
cuneothalamic and the thalamocortical group I relay cells (Rosén 1969 a, b) will provide a basis for an attempt to answer the question.

Three types of excitation of cuneothalamic group I relay cells are described by Rosén. The majority of the cells were activated by group I afferents only. Two other types received excitatory convergence from group I and cutaneous afferents, or from group I and group II afferents. It is also possible that all three types of afferents converged with excitation on some cells. Accepting the existence of the last mentioned type of cell, the percentages given on the co-activation from cutaneous and group II afferents leave a small but perhaps significant group of cuneothalamic group I cells with convergence only from group I and group II, or only from group I and cutaneous afferents.

Further indirect evidence for the assumption that the cutaneous and the group II afferents did not converge on the same cuneate group I relay cells can be obtained from an analysis of the afferent connexions to thalamic group I cells. In them one would expect to find the same type of excitatory convergence from cutaneous and group II afferents as in the corresponding cuneothalamic neurones. If cuneothalamic group I relay cells to a large extent were co-activated by cutaneous and group II afferents, one would expect also the thalamic group I cells to receive input from these two types of afferents. This was, however, not the case. Thalamic cells co-excited by group I and group II afferents were instead intermingled with other neurones receiving group I excitation. Inhibitory mechanisms selective for the cutaneous activation of thalamic cells co-excited by group I and group II afferents could offer an explanation of this finding. This interpretation is, however, not consistent with the observation that the group I thalamocortical relay cells showed an increase in excitatory convergence from skin afferents when compared with group I cuneothalamic cells. The excitatory input from group II afferents to the thalamic group I cells again decreased by 50 % in relation to that observed in the main cuneate group I relay cells. This reasoning thus leads to the conclusion that co-excitation from skin and group II afferents occurred mainly on different group I cuneothalamic cells.

The pattern of co-activation from skin and group II muscle afferents of cuneothalamic and thalamocortical group I neurones accordingly gives a positive answer to the question raised above. A functional differentiation of the group I projection into following components seems justified: some cells are exclusively linked to a group I path, other cells are activated by a group I and a cutaneous path, and still others are connected to a group I and a group II path. There may also be cells influenced by all three types of paths.
Additional information on the organization of the group I system at the thalamic level is gained from an analysis of the antidromic invasion of group I thalamic cells from the ASSS and Pcd group I loci, taken as an indication of bifurcating thalamocortical axons (Anderson et al. 1966, Rosén 1969 b). An identical interpretation has been given for observations on other ascending systems (Rose and Woolsey 1958, Darian-Smith 1964, Andersen, Andersson and Landgren 1966, Rowe and Sessle 1968, Manson 1969). The majority of the group I thalamocortical cells were, however, antidromically activated only from Pcd, a small part of them from ASSS, and a few cells presumably had bifurcating axons to both cortical group I loci. These findings suggest three populations of thalamocortical group I cells, projecting both to Pcd and to ASSS, only to Pcd, and only to ASSS. The three alternative paths are shown in Fig. 3 A—C (solid lines, grp I).

**Fig. 3** Diagrams of ascending forelimb group I and cutaneous paths to Pcd and ASSS group I cells.

A. Solid lines (grp I) indicate the group I path with bifurcating thalamocortical axons projecting to Pcd and ASSS. Disynaptically linked excitatory convergence from two cutaneous paths (interrupted lines, cut.b and cut.c) to the Pcd and ASSS cells could explain the increasing convergence from cutaneous afferents at consecutive levels of the group I path. The cutaneous path marked cut.a is that described by Rosén (1969 a, b).

B. Independent group I path to ASSS (grp I) with convergence from a fast cutaneous path (cut.a) explains the monosynaptic excitation of ASSS group I cells by thalamocortical axons. The disynaptically linked cutaneous path (cut.b) described by Rosén (1969 a, b) may also converge with excitation on ASSS group I cells.

C. Disynaptically linked cutaneous excitation of Pcd group I cells—and also of group I cells in the main cuneate and thalamic nuclei (Rosén 1969 a, b)—could be achieved by the cutaneous path (cut.b). The increased convergence of excitation from cutaneous afferents at cortical level could be accounted for by the alternative cutaneous path (cut.a).
In the following it will be hypothesized how excitation from low threshold cutaneous and group II afferents could be linked to the three alternative group I thalamocortical paths and how cutaneous and group II paths might converge with excitation on the ascending group I projection.

Forelimb cutaneous afferents are known to project to the cerebral cortex by way of the dorsal column-lemniscal path and the spinocervico-lemniscal tract, SCLT. Norrsell and Voorhoeve (1962) showed that impulses in the forelimb SCLT arrive earlier to the cerebral cortex than impulses in the dorsal column, DC, path. Andersson (1962) and Oscarsson and Rosén (1966) failed to confirm this observation. This may be due to the fact that the location of the spinal fascicle transection was not the same in the later studies. Whitehorn, Morse and Towe (1969) altogether question forelimb SCLT contributions to short latency cortical responses.

Considering the cutaneous paths converging with excitation on group I cells, several alternatives are conceivable. These are diagrammatically shown in Fig. 3 (interrupted lines). ASSS and Pcd cells monosynaptically activated by bifurcating group I- and disynaptically by cutaneous thalamocortical afferents may be provided with afferent connexions according to alternative A. Cutaneous afferents (cut. a) converging with disynaptic excitation on group I cells in the main cuneate nucleus and additional thalamocortical or corticocortical cutaneous paths could explain the increased excitatory convergence from cutaneous afferents to cortical group I cells. The cutaneous paths converging on cortical group I cells in Pcd and ASSS (cut. b and c) are presumably not identical, because the ASSS cells received a higher degree of excitation from cutaneous afferents than corresponding Pcd cells (Oscarsson et al. 1966, Silfvenius 1972).

ASSS group I cells monosynaptically excited by thalamocortical group I and cutaneous afferents would receive activation via independent thalamocortical paths as shown in Fig. 3 B (cut. a). Cutaneous paths converging with excitation on such ASSS group I neurones could belong either to the DC-lemniscal or the SCLT path. As illustrated in Fig. 3 B these ASSS cells may in addition receive cutaneous activation from cuneate and thalamic group I cells with disynaptic (cut. b) excitatory convergence from skin afferents (Rosén 1969 a, b, Silfvenius 1972).

The group I Pcd cells monosynaptically excited by an independent group I thalamocortical path could receive disynaptic co-activation from cutaneous afferents as diagram C of Fig. 3 suggests. As mentioned by Rosén (1970) the increased convergence from cutaneous afferents on Pcd group I cells, as compared to that found at the main cuneate and thalamic levels, could be explained by combined excitation via the two alternative cutaneous paths (cut. a and b) illustrated in Fig. 3 C. The same
might be true for the Pcd cells monosynaptically activated by a bifurcating group I thalamocortical path (cf. Fig. 3 A).

The diagrams of Fig. 3 obviously give the simplest alternatives. More complex paths may be conceived, e.g. one may assume bifurcation of the thalamocortical cutaneous paths to the two cortical group I areas. As, however, the cutaneous input to Pcd and ASSS group I cells differs quantitatively, an inhibition of the cutaneous input to Pcd would then have to be assumed.

By which fast paths do forelimb group II afferents project to the cerebral cortex? Muscle afferents excitable at group II strength and projecting to the cerebral cortex ascend in the dorsolateral fascicle, DLF, Landgren et al. 1967). The course of the DLF group II forelimb path is undefined and it is not known whether or not this path is a subdivision of the spinocervical tract, SCT. Lundberg and Oscarsson (1961) did, however, demonstrate a small response on low group II intensity stimulation of hind limb muscle afferents in DLF axons travelling with the SCT.

Exclusive group II excitation of cells in the main cuneate nucleus has been described. The incidence in the investigated sample was, however, so low that the finding was not considered to indicate a separate group II path. Excitation from group II afferents was also found in cutaneous relay cells of the same nucleus (Rosén 1969 a). Group II afferents converged with excitation on group I thalamocortical cells at latencies suggesting monosynaptic linkages from medullothalamic axons. They also activated other thalamic cells which were co-activated by skin afferents. These cells were located in a zone dorsal to the forelimb group I relay zone (Rosén 1969 b).

The latencies of the group II potentials recorded in some cells suggest a fast group II path to the Pcd and ASSS regions (Grampp and Oscarsson 1968, Silfvenius 1972).

The group II excitation of ASSS cells monosynaptically activated by bifurcating or separate group I thalamocortical fibres is presumably mediated by a separate group II path, since corresponding Pcd group I cells were relatively unaffected by group II afferents. The group II paths to ASSS group I cells may ascend in DC and in DLF. The group II paths to Pcd cells activated by unbranched or bifurcated group I thalamocortical axons could be inhibited at thalamic level (Andersen, Eccles and Sears 1964 a). Such inhibition would not affect other Pcd cells activated after short latency by group II afferents (Grampp and Oscarsson 1968).

Group II forelimb muscle afferents thus have access to fast paths projecting to the Pcd and ASSS group I loci. It remains to investigate if the observed group II effects have been mediated by axons from secondary endings in muscles.
B. FUNCTIONAL CONSIDERATIONS

The Pcd cells monosynaptically activated by thalamocortical group I fibres are assumed to be inhibitory neurones. The assumption is based on the observation that cells with latencies suggestive of disynaptic linkages with thalamocortical group I fibres are seldom encountered, and that a large group of inhibited cells have latencies suggesting disynaptic linkages with thalamic fibres (Oscarsson et al. 1966, Grampp and Oscarsson 1968).

A similar functional interpretation for ASSS cells with latencies suggesting monosynaptic activation by thalamocortical group I axons cannot a priori be presumed, as there are other cells excited at latencies suggesting di- or polysynaptic activation from thalamic relay cells (Silfvenius 1972). In the group I ASSS locus the group I information is therefore to a considerable degree forwarded as excitation. It is unknown which cortical mechanisms this excitation subserves. The ASSS group I locus is located in sensory area 2 pri (Hassler and Muhs-Clement 1964) and its function could therefore be related to sensory mechanisms. The role of group I afferents in sensory perception has, however, been considered insignificant on the grounds that electrical stimulation of cut muscle nerves at group I intensity has failed to influence instrumental conditioning reflexes (Swett and Bourassa 1967 b), the EEG, and the behaviour of cats (Giaquinto, Pompeiano and Swett, 1963). The ASSS group I locus may, however, be involved in descending control mechanisms. The observations of Abrahams (1969) may indicate that the group I forelimb projection to the ASSS region participates in cortical mechanisms integrating postural reflexes.

In the cat the forelimb group I projections are distributed to area 3a, area 2 and to area 4 γ within the first sensorimotor cortex (Oscarsson and Rosén 1963, Silfvenius 1968, Hassler and Muhs-Clement 1964). The projection to area 3a agrees well with that recently found in the monkey (Phillips, Powell and Wiesendanger 1971). In this animal short latency group I forelimb responses have, however, not been obtained in the investigated part of area 4. This may imply a species difference or that group I forelimb afferents project to parts of area 4 not yet investigated in the monkey.
V. PROJECTIONS TO THE CEREBRAL CORTEX FROM GROUP I HIND LIMB AFFERENTS

A. CORTICAL PROJECTION FIELDS

Electrical stimulation of group I hind limb afferents evokes short latency potentials in the contralateral cerebral cortex of the cat. Initial surface positive group I hind limb responses in the first sensorimotor cortex may be recorded in two areas of the postsigmoid gyrus as illustrated in Fig. 4. Vertically hatched areas show diagrammatically the regions in which group I hind limb potentials have been recorded and the relations of the projection fields to the cytoarchitecture of the gyrus. One projection area, located on the dorsal surface of the gyrus is denoted the dorsal group I hind limb locus. It is situated rostromedially to and partially overlapping the forelimb Pcd group I projection. Group I hind limb responses can also be recorded in an area on the medial surface of the hemisphere, here called the medial group I hind limb locus. The dorsal locus is found mainly in area 3a, i.e. in the border zone of the motor cortex, area 4 γ. The medial group I hind limb locus is also located in area 3a near the border of area 4 γ. It sometimes extends caudally into sensory area 1 (Hassler and Muhs-Clement 1964, Landgren and Silfvenius 1969). In addition to these projection fields, group I hind limb potentials may also occasionally be recorded in the lower bank of the ASSS and at times even in the ectosylvian gyrus. The latencies of the responses in the two last mentioned regions have been somewhat longer than those in the postsigmoid gyrus (Landgren et al. 1967, Silfvenius 1972, H. Silfvenius, unpublished observations).

Hind limb group I afferents thus project to several regions in the cerebral cortex of the chloralose anesthetized cat. Their projection pattern resembles that of the corresponding forelimb afferents.

Zonal convergence has been observed between the group I hind limb projection fields and those of other hind limb proprioceptive and exteroceptive afferents. The projections to the postsigmoid gyrus from afferents of deeply located Pacinian corpuscles (interosseous nerve) are illustrated in Fig. 4 D (Silfvenius 1970 b). Low threshold joint afferents (posterior knee joint nerve) project to areas diagrammatically shown in Fig. 4 C (Körner and Landgren 1969, F. Clark, S. Landgren and H. Silfvenius, unpublished observations). Their projection pattern resembles that of low threshold skin afferents (sural nerves) shown in Fig. 4 B with a fourfold distribution to the postsigmoid gyrus; two fields overlapping with the dorsal and medial group I hind limb loci, and two additional ones located.
Fig. 4 Diagrams of projections to the cerebral cortex from hind limb proprioceptive and exteroceptive afferents.

A. Projections from group I hind limb afferents (vertical hatching) to the medial and dorsal postsigmoid cortex. The dorsal group I hind limb locus overlaps marginally with that of the forelimb afferents in Pcd (encircled area). The forelimb group I projections to the ansate and the ASSS regions are not shown.

B. The rostral projection fields of low threshold skin afferents (black areas) overlap with the group I hind limb loci; additional fields are located caudally to the former. The sural nerves were stimulated.

C. The projection fields from low threshold joint afferents (oblique hatching) overlap with the group I hind limb loci and with the caudal fields of the cutaneous afferents (cf. Fig 4 B). The posterior knee joint nerve was stimulated.

D. The projection fields of proprioceptive Pacinian afferents (horizontal hatching) are located somewhat rostrally to those of the group I hind limb afferents, with which they overlap. A dual dorsal and medial projection from these Pacinian afferents has not been observed. The interosseous nerve was stimulated.

The cytoarchitectonically defined regions are marked with thin lines according to Füssler and Muhs-Clement (1964) as in Fig. 1. Abbreviations as in Fig. 1.

caudally to these loci (S. Landgren and H. Silfvenius, unpublished observations). Oscarsson and Rosén (1966) described a dual projection from forelimb skin afferents to the first sensorimotor cortex.
B. THE GROUP I HIND LIMB CEREBRAL PATH

The course of the group I hind limb cerebral path is diagrammatically illustrated in Fig. 5. The path contains four synaptic relays located segmentally in the spinal cord, in the medulla, in the thalamus and in the cerebral cortex respectively. Group I hind limb responses in the post-sigmoid cerebral cortex can be evoked after removal of the cerebellum and the path is therefore not relayed there. Its course will be described below in some detail.

Primary group I hind limb afferents enter the segmental grey matter of the spinal cord to synapse on cells of hitherto undetermined location. It is likely that cells activated by group I primary afferents, entering in dorsal roots L₇ and S₁, are located in the grey matter at L₃ level as most of their axons enter the ipsilateral DLF at this level. In the upper cervical cord the secondary axons of the path occupy a superficial portion...

---

Fig. 5 Diagram of the ascending group I hind limb cerebral path.
(1) Primary group I hind limb afferents (investigated with L₅—S₁ fibres) ascend in the DC and synapse presumably in the grey matter on segmental cells (2) with axons entering the ipsilateral DLF at about L₃ level. The secondary axons ascend to the medulla oblongata and make synaptic contacts with cells in the ipsilateral nucleus Z of Brodal and Pompeiano (3). It is unknown whether or not DSCT collaterals are afferents to nucleus Z. The efferents of nucleus Z cross the midline and ascend in the medial lemniscus and enter the contralateral thalamic nucleus VPL₁ (4). Thalamocortical group I hind limb fibres project to the two group I loci in the post sigmoid gyrus and presumably also to the ASSS and the ectosylvian region. No details are known about the branching of the thalamocortical group I hind limb fibres.
VPLₘ = medial part of VPL
VPM = nucleus ventralis posterior medialis thalami.
of the DLF as do the axons of the dorsal spinocerebellar tract, DSCT, (Beck 1927, Grant 1962, Holmqvist and Oscarsson 1963, Landgren and Silfvenius 1969, 1971). The third order neurones of the path are located in the ipsilateral medullary nucleus Z of Brodal and Pompeiano (1957). This is a small and superficial nucleus situated between the rostral pole of the gracile and the caudal pole of the medial vestibular nuclei, bordering medially to the lateral recess of the fourth ventricle. The anatomical study of Pompeiano and Brodal (1957) showed that some spinal afferents to nucleus Z passed through a neighbouring nucleus in the medulla, nucleus X, others passed dorsally to this nucleus and entered directly into nucleus Z from the restiform body. A number of lateral fascicle fibres passed through nucleus Z and continued to the medial part of the ipsilateral gracile nucleus.

Nucleus Z receives lateral fascicle afferents from levels caudal to Clarke's column as shown in anatomical studies (Pompeiano and Brodal 1957, Busch 1961, Brodal and Angaut 1967). Such a projection has not been confirmed with physiological technique. Hand (1966) reported that nucleus Z receives some lumbar and sacral DC afferents.

The rostrocaudal and mediolateral extents and the depth of the nucleus Z determined physiologically with group I hind limb input, are in good accord with its extents anatomically defined (Brodal and Pompeiano 1957, Hauglie-Hanssen 1968, Landgren and Silfvenius 1971). The cells of nucleus Z are uniform, medium sized with rather sparcely branched dendrites. Cell axons have not been demonstrated (Brodal and Pompeiano 1957, Hauglie-Hanssen 1968). Due to its superficial location, negative field potentials evoked by stimulation of group I hind limb afferents may be recorded from the exposed medullary surface over the nucleus.

Recordings from single cells in nucleus Z have defined some of them as medullothalamic group I hind limb relay cells. The latencies of their action potentials, evoked by group I hind limb afferents, suggest that some of them are monosynaptically and other di- or polysynaptically linked to the secondary DLF axons of the path. The thresholds of activation indicate connexions mainly with Ia afferents, but at times co-excitation from Ib, group II or from cutaneous fibres has been observed. Excitation of nucleus Z cells exclusively from group II or exclusively from cutaneous afferents has occasionally been seen. The latencies of these responses suggest monosynaptic linkages with secondary fibres (Landgren and Silfvenius 1971, S. Landgren and H. Silfvenius, unpublished observations). The nucleus Z cells were similar to the group I cells of DSCT, the main cuneate, and the external cuneate nuclei in the sense that they received excitation from one muscle nerve and thus had restricted peripheral fields (Oscarsson 1965, Rosén 1969 a, Cooke et al. 1971, Landgren and Silfvenius 1971).
Fourth order cells of the group I hind limb cerebral path are located in the contralateral thalamic nucleus ventralis posterior lateralis, VPL. The latencies of thalamic focal potentials suggest monosynaptic activation of VPL cells by group I hind limb medullothalamic fibres (Landgren and Silfvenius 1970). Anatomical studies with destruction of nucleus Z show degenerating axons passing ventromedially in the medial lemniscus, terminating rostrally in a dorsolateral portion of VPL, i.e. in the lateral part of VPL (=VPL, of Rinvik 1968 a). Terminal degeneration has in addition been found in the ventrolateral and dorsal portions of nucleus ventralis lateralis thalami, VL, (Boivie, Grant and Silfvenius 1970). Antidromic activation of group I nucleus Z cells has, however, also been achieved with stimulation of more medial thalamic structures. This indicates that some axons or axon collaterals of nucleus Z cells take another course through the thalamus than those that follow the lemniscal route. Unpublished anatomical observations do, in fact, substantiate this as they show a projection of nucleus Z efferents to the thalamic nucleus centrum medianum (J. Boivie, G. Grant and H. Silfvenius, unpublished observations). Thalamic group I hind limb responses have remained after removal of the cerebellum (S. Landgren and H. Silfvenius, unpublished observations).

Fifth order neurones of the group I hind limb cerebral path are located in the two earlier mentioned loci of the postsigmoid gyrus, as the latencies of the focal group I hind limb cortical potentials suggest. It is possible that both bifurcating and independent group I hind limb thalamocortical paths project to the two cortical loci. The spatial overlap of group I hind limb focal potentials in the loci suggests that the cortical group I neurones receive excitatory convergence from several muscle nerves. It has been concluded that both Ia and Ib afferents contribute to the cortical group I hind limb potentials in the postsigmoid gyrus.

Common for cortical, thalamic and medullary group I hind limb potentials is that they are all evoked by activity in axons located superficially in DLF at C1 level (Landgren and Silfvenius 1969, 1971, S. Landgren and H. Silfvenius, unpublished observations H. Silfvenius, unpublished observations). The afferent connexions to single cortical and thalamic group I hind limb cells have not yet been studied systematically.

The dual projection from group I hind limb afferents to the postsigmoid gyrus as found in the chloralose anesthetized cat, cannot be considered to substantiate the "pre- and postaxial organization" advocated by Woolsey's group (Haynes and Woolsey 1944). According to Woolsey, the hind limb projection to the postsigmoid gyrus is differentiated so, that afferents from preaxially located peripheral exteroceptive receptors project to the dorsal, and afferents from postaxial sensory endings to the medial surface of the gyrus. The present investigations show on the contrary that both
"pre- and postaxial" group I hind limb afferents project to the two loci of the postsigmoid gyrus. They further show that the projections from hind limb cutaneous and joint afferents are even duplicated on the dorsal and medial surfaces of the postsigmoid gyrus, each area receiving at least "postaxial" projections (cf. Fig. 4 B and C).

VI. DISCUSSION OF THE GROUP I HIND LIMB PROJECTION TO THE CEREBRAL CORTEX

A. THE GROUP I HIND LIMB CEREBRAL PATH AND THE DORSAL SPINOCEREBELLAR TRACT

As the group I hind limb cerebral path has a course similar to that of the DSCT the question arises whether or not the spinal component of the group I hind limb cerebral path is identical with the DSCT.

Group I muscle afferents from the ipsilateral hind limb are relayed in Clarke's column (Curtis, Eccles and Lundberg 1958). This extends caudally to the L3-5 level (Rexed 1954, Hongo, Okada and Sato 1967). It has further been shown that group I hind limb axons leave DC at the L3-5 level (Oscarsson 1957 a). Since secondary fibres of the group I hind limb cerebral path must have contributed to the DLF responses investigated by Oscarsson, one may expect a similar course and segmental relay also for this path. A reinvestigation of its segmental transfer from DC to DLF was therefore made with group I hind limb potentials in the cerebral cortex as an index, and it was indeed found that most of the primary axons of the group I hind limb cerebral path entered DLF at L3 level. The exact level of entry was not defined because the lesions made included both the DC and the segmental grey matter (Landgren and Silfvenius 1971). Such lesions may have interrupted primary DC and secondary grey matter axons. The exact location of the segmental relay of the group I hind limb cerebral path is therefore still unknown.

Of relevance in this context is the observation of Lundberg and Oscarsson (1960) that about one fourth of segmental DSCT cells could not be antidromically activated from the cerebellum. This may either indicate a lack of access to DSCT fibres by the cerebellar stimulus, or a DLF path not projecting to the cerebellum.
If the group I hind limb cerebral path is identical with the DSCT the afferent input to nucleus Z should be provided by DSCT collaterals. There is anatomical evidence of DSCT collaterals branching off in the restiform body (Lorente de Nó 1924). Pompeiano and Brodal (1957) remarked that numerous fibres entering nucleus Z were coarse, an observation which, on the other hand, may indicate that afferents to nucleus Z constitute a separate path.

Another approach to the problem of the relation between the DSCT and the group I hind limb cerebral path is to compare the excitatory convergence pattern of segmental DSCT cells with that of nucleus Z cells. Such a comparison reveals that the excitation pattern from muscle and skin afferents, on the whole, is identical in segmental DSCT and in nucleus Z cells (Lundberg and Oscarsson 1960, Landgren and Silfvenius 1971, S. Landgren and H. Silfvenius, unpublished observations). These findings are thus compatible with the alternative that nucleus Z cells are activated by DSCT collaterals.

There is anatomical and physiological evidence for DLF axons from levels caudal to Clarke’s column which are not part of the DSCT (Lundberg and Oscarsson 1960, Grant 1962). It is further important to note that degenerating terminals were observed in nucleus Z after lateral fascicle lesions caudal to Clarke’s column (Pompeiano and Brodal 1957, Busch 1961, Brodal and Angaut 1967). These findings could therefore be due to a transection of:

a) an ipsilateral tract with segmental cells located at low lumbar and sacral levels and with primary afferents ipsilateral to nucleus Z,
b) secondary afferents of contralaterally located segmental cells which receive contralateral primary afferents, or
c) secondary afferents of ipsilateral segmental cells which are connected to contralateral primary afferents.

Alternative a is compatible with the existence of an undefined DLF tract independent of the DSCT and proceeding to nucleus Z. The spino-cervical tract is excluded from this alternative on anatomical and physiological grounds. Low lumbar DLF lesions of the SCT would not cause degeneration in nucleus Z, as the SCT relays in the lateral cervical nucleus (Rexed 1951, Rexed and Brodal 1951, Grant, Boivie and Brodal 1968). Further, the SCT does not mediate activity in group I axons (Lundberg and Oscarsson 1961).

The ventral spinocerebellar tract, VSCT, would fit alternative b (Oscarsson 1957 b, Lundberg and Oscarsson 1962, Burke, Lundberg and Weight 1971). It has not been investigated whether nucleus Z has input from the VSCT and this possibility therefore remains open.

Alternative c provides a possibility for a path to nucleus Z which may
have support from physiological evidence. Low lumbar and sacral segmental cells have been described which are connected to contralateral primary afferents (Curtis, Krnjevic and Miledi 1958, Sprague 1958, Frank and Sprague 1959, Holmqvist and Oscarsson 1963, Edisen 1967). Occasionally, monosynaptic excitation from contralateral group I primary fibres of DSCT units has been reported (Oscarsson 1957 b, Lundberg and Oscarsson 1960). At present no information is, however, available concerning the group I input to the cerebral cortex from the ipsilateral hind limb.

In summary it may be stated that there are striking similarities between the group I hind limb cerebral path and the DSCT with regard to their spinal courses and the functional properties of segmental DSCT and nucleus Z cells. Some findings do, however, suggest that the two paths are independent, but further experimentation is required to solve this problem.

B. GROUP II EXCITATION OF THE GROUP I HIND LIMB CEREBRAL PATH

As judged from cortical surface recordings the organization of the afferent input to the postsigmoid group I hind limb loci is characterized by group I responses located in central zones which in their peripheries include potentials evoked by skin and by group II muscle afferents. The cortical potentials evoked by the latter afferents thus tend to have their amplitude maxima located in the periphery of the group I hind limb responses (Landgren and Silfvenius 1969). Cortical responses evoked by stimulation of high threshold muscle afferents have earlier been described (Mountcastle, Covian and Harrison 1952). McIntyre (1953, 1962 a) concluded that group II afferents could evoke cortical responses. It is possible that some of the recordings performed in the early studies were made in regions surrounding the dorsal group I hind limb locus. In the ASSS region again, hind limb group II afferents project to areas receiving group I fore- and hind limb projections, as well as to the upper cortical bank of ASSS (Landgren et al. 1967, Silfvenius 1972). The latencies of the ASSS group II hind limb potentials suggest a fast path to this cortical region. The group II hind limb potentials recorded in the postsigmoid gyrus had longer latencies and were presumably evoked via more complex paths (Landgren and Silfvenius 1969).

By which paths could activity in hind limb group II afferents reach the cerebral cortex? Responses have been observed in nucleus Z, with latencies suggestive of monosynaptic activation by secondary ascending group II fibres from the hind limb (S. Landgren and H. Silfvenius, unpublished observations). Such potentials may have been evoked by volleys
in an independent DLF path mediating exclusively group II information. It is, however, equally possible that such a path mediates activity also from cutaneous and other receptors. If so, it might be identical with a path described by Lundberg and Oscarsson (1961) which was activated at short latency by flexion reflex afferents, FRA, and did not have a cerebellar termination. If, on the other hand, DSCT collaterals provided the group II activation of nucleus Z cells, this activation could have been mediated by the FRA subdivision of the DSCT (Lundberg and Oscarsson 1960).

Stimulation of group II hind limb afferents evokes potentials in the contralateral thalamus. Some of these potentials have been recorded in the group I hind limb relay zone. Transections in the lateral fascicle at C1 level have abolished thalamic group II potentials (S. Landgren and H. Silfvenius, unpublished observations).

Norrsell and Wolpow (1966) found hind limb group II responses in the cerebral cortex to be mediated by DLF and DC pathways. Unpublished observations from this laboratory confirm that combined DLF—DC transections leave initially surface negative group II potentials recordable in the cerebral cortex.

The available evidence therefore suggests that DC and lateral fascicle pathways mediate group II excitation to the ascending group I hind limb cerebral path, though it is not known whether the group II afferents converge with excitation or inhibition on single group I hind limb cells in the thalamus and in the cerebral cortex. If the short latency group II excitation observed in axons travelling with the SCT significantly contributes to the thalamic and cortical group II responses is unknown (Lundberg and Oscarsson 1961).

The receptors of the group II hind limb afferents projecting to the cerebral cortex have not been defined with natural stimulation in the present investigation.

C. CUTANEOUS AFFERENTS CONVERGING ON THE GROUP I HIND LIMB CEREBRAL PATH

Cutaneous afferents converge with excitation on the group I hind limb cerebral path at the nucleus Z, thalamic and cortical levels (Landgren and Silfvenius 1969, 1970, 1971). The cutaneous excitation may be provided by a separate DLF path, by DSCT collaterals, by the SCLT and by DC afferents.

Impulses in the SCLT reach the cerebral cortex faster than do impulses in the DC path (Mark and Steiner 1958, Norrsell and Voorhoeve 1962). A thalamic projection from SCLT has been demonstrated in physiological

Studies have been performed to determine the spinal fascicular location of the ascending projections from functionally defined cutaneous receptors. The cutaneous subdivision of the DSCT contains afferents from endings responding to movement of hairs, light touch and pressure and to nociceptive stimuli (Lundberg and Oscarsson 1960). Mann and Tapper (1970) have identified cutaneous afferents of the DSCT as coming from rapidly adapting guard hair, down hair and tylotrich units, and from slowly adapting Type I receptors. If nucleus Z receives cutaneous input via DSCT collaterals it would originate from these receptor types.

Cutaneous afferents reaching nucleus Z have not been defined with adequate stimulation.

At the thalamic and cortical levels cells in the group I hind limb cerebral path may be co-activated by SCT units responding to movement of guard hairs and skin pressure, movement of tylotrich hairs, movement of all hairs and skin pressure and to pressure and pinch of the skin (Brown and Franz 1969). Additional activation at the thalamic and cortical levels from DC cutaneous afferents is likely to occur. The hind limb cutaneous afferents ascending in DC up to the medulla have been found to originate from slowly adapting Type I and Type II-, rapidly adapting Pacinian-, guard hair (G\textsubscript{1} and G\textsubscript{2}), tylotrich hair-, field receptor- and pad unit afferents (Brown 1968, Whitehorn, Cornwall and Burgess 1971).

The observations referred to above thus suggest that low threshold cutaneous afferents from the hind limb may co-activate neurones of the group I hind limb cerebral path via many alternative pathways. An increasing integration of activity from convergent cutaneous paths is likely to take place at consecutive levels of the group I hind limb cerebral path.

D. CONTRIBUTIONS FROM PACINIAN- AND LOW THRESHOLD JOINT AFFERENTS

It was shown in Fig. 4 that there is a zonal overlap of the projections to the postsigmoid cerebral cortex from hind limb group I-, low threshold joint- and Pacinian afferents. In the thalamic group I hind limb relay zone, occasional responses evoked by activity in low threshold joint afferents have been recorded (Landgren and Silfvenius 1970). An interesting difference has been observed in the spinal course between the ascending Pacinian and the low threshold joint paths from the hind limb. Pacinian afferents thus ascend in the DC (McIntyre 1962 b, Norrsell and Wolpow 1966, Silfvenius 1970 b) while the low threshold joint afferents mainly travel in the DLF (Gardner 1967, Burgess and Clark 1969 b, Körner and
Landgren 1969, F. Clark, S. Landgren and H. Silfvenius, unpublished observations). It would be of interest to investigate whether low threshold joint afferents project to nucleus Z.

E. DO 1b HIND LIMB AFFERENTS PROJECT TO THE CEREBRAL CORTEX?

It has been stressed above (cf. section II, C 1) that a distinction is made between the terms "Ia and Ib afferents" and "primary spindle and tendon organ afferents". In the literature this distinction is often neglected and the terms are used synonymously. It is obvious that both the Ia and Ib component of the group I compound action potential may contain primary spindle and tendon organ afferents and axons from other receptors. The question now asked is: do Ib hind limb afferents project to the postsigmoid cerebral cortex?

Electrical stimulation of hind limb muscle nerves which provide a good subdivision of the Ia and Ib volley components are suitable for an analysis of this problem. Stimulating such nerves and comparing the shape and the amplitude of the cortical potential evoked during graded electrical stimulation of muscle nerve afferents Landgren and Silfvenius (1969) concluded that hind limb Ib afferents do indeed project to the postsigmoid cerebral cortex. The conclusion was based on the following observations:

a) the amplitude of the cortical focal potential increased with that of the group I afferent volley in such a way that the two observed amplitude levels of the cortical response were closely related to the amplitudes of the Ia and the maximal group I volley spikes, respectively. It seems likely that mainly Ib afferents contributed to the increase in amplitude of the cortical focal potential since the amplitude continued to grow above maximal Ia strength of stimulation. Also some high threshold Ia afferents, included in the Ib component of the compound action potential, might have contributed to the increase in the amplitude of the cortical "Ib response".

b) the latency of the "Ib response", at times seen as an indentation on the rising phase of the cortical potential, was 3 to 5 msec longer than that of the Ia response. This difference could be accounted for by differences in conduction velocity between Ia and Ib afferents.

c) when using the double volley technique of Bradley and Eccles (1953)—the Ib volley was arranged to fall in the axonal refractory period of the Ia volley—it was observed that the cortical group I hind limb response, evoked by the separated Ia and Ib volleys, decreased in amplitude when the Ib volley was left out.
d) independent activation of Ia and Ib fibres of the same nerve (with two bipolar stimulation electrodes) showed a cortical response contribution from Ib afferents activated by a single shock to the nerve also when the Ia path was driven refractory by repetitive stimulation.

The conclusion of Landgren and Silfvenius that hind limb Ib afferents project to the cerebral cortex can be criticized with the following arguments:

a) Group II afferents may have contributed to, or caused the "Ib response" evoked by maximal group I stimulation strength as a certain number of group II afferents may be excited at this stimulus strength or even below (Eccles et al. 1957, Coppin et al. 1970). On the other hand, the group II afferents do not, to any considerable degree, project to the "center" of the cortical dorsal group I hind limb locus from which the recordings were made. Further, the latencies of the group II hind limb responses in the dorsal postsigmoid cerebral cortex are longer than those of the "Ib response" (Landgren and Silfvenius 1969).

b) The growth of the group I hind limb focal potential with increasing group I strength of stimulation could be due to the "opening" of a collateral Ia path, requiring a higher degree of spatial summation. One example of a collateral Ia path is a cerebello-thalamo-cortical Ia loop. Recent anatomical studies show that the DSCT projects to the cerebellar nuclei (Matsushita and Ikeda 1970). Ia volleys relayed via the cerebellar nuclei would require about 2 to 5 msec to travel from the nuclei to the cerebral cortex (Uno, Yoshida and Hirota 1970). Therefore, if this collateral Ia path contributes to the cortical response evoked by the medullothalamic lemniscal route, its amplitude contribution to the cortical potential could commence already with the Ia response. If, on the other hand, this collateral Ia path required a higher degree of spatial summation, its amplitude contribution to the cortical response could coincide with the "Ib response". As the test on this point was not made on an animal with its cerebellum removed the possibility of a cerebello-thalamo-cortical Ia loop contribution cannot be excluded.

c) A dorsal root- or funicle reflex could have accounted for the "Ib response". This possibility is probably ruled out by the fact that the minimal central delay for a dorsal root potential, DRP, evoked by group I muscle afferents, is 4 msec (Eccles 1964). A DRP volley generated segmentally 4 msec later than the direct group I excitation of segmental relay cells would reach the cerebral cortex at least 4.5 msec later (=minimal central delay + synaptic delay) than the volley travelling in the "direct path". The latencies of the "Ib responses" were usually less than 4 msec (cf. Landgren and Silfvenius 1969, Table 1).
d) Pacinian afferents might have evoked the cortical "Ib response". This argument is refuted by the findings of Landgren and Silfvenius (1971) that a Th₈ transection of the DC did not decrease the amplitude of a cortical group I hind limb response evoked by maximal group I stimulation. Pacinian afferents from the hind limb ascend in the DC as pointed out above (cf. Section VI, D).

In summary it may be stated that it is likely that hind limb Ib afferents excite cells in the postsigmoid gyrus of the cerebral cortex, but the question is not definitely settled as yet. The present facts do not exclude the possibility that group II hind limb afferents or a 1a collateral path might have been responsible for the "Ib response" evoked in the cerebral cortex.

If the "Ib response" was activated by tendon organ afferents remains to investigate. The observations of Lundberg and Oscarsson (1956), Smith (1969) and of Rosén and Sjölund (1969) show that tendon organ afferents do indeed project to supraspinal structures.

F. FUNCTIONAL CONSIDERATIONS

The present knowledge of the organization of the group I hind limb cerebral path is based mainly on recordings of mass activity. Such recordings provide a basis for further unitary studies, which will give a more complete picture of the organization. The unitary studies could feasibly include analyses of both afferent and efferent elements to suggest which mechanisms the group I hind limb information subserves at the segmental, medullary, thalamic and cortical levels. Certain general aspects of the cortical organization of the group I hind limb projection to area 3a will be dealt with here.

The group I hind limb input to the postsigmoid gyrus (cf. Fig. 4 A) is located in the cytoarchitectonically defined area 3a (Hassler and Muhs-Clement 1964). This is also true for the proprioceptive Pacinian input from the hind limb (cf. Fig. 4 D), while those from low threshold skin and joint afferents are zonally arranged both in area 3a and caudally to this area, i.e. in sensory area 1 (cf. Fig. 4 B and C). As area 3a borders the motor area 4 γ, it can be asked whether cells in area 3a, activated by group I hind limb afferents relay their information to pyramidal cells of area 4 γ or whether they have an output of their own, either to the spinal segments or to other cortical or subcortical structures.

If hind limb group I excitation of neurones in area 3a is forwarded to area 4 γ, which may be assumed in analogy with the finding that group I forelimb potentials have been recorded in area 4 γ (Silfvenius 1968), this would imply that a possibility exists to demonstrate a group I hind limb
projection to the motor cortex. No group I hind limb potentials have, however, been recorded in those parts of the motor cortex directly accessible to surface recordings, but, on the other hand, the motor cortex hidden in the upper bank of the cruciate sulcus has not been investigated. Recordings in the hidden upper bank of the cruciate sulcus would therefore be worthwhile to perform in order to find out if a group I hind limb projection to this area exists, and if it is directly linked to thalamocortical axons or relayed via the other group I hind limb cortical loci of the postsigmoid gyrus. Experiments have hitherto mainly been concerned with defining the afferent connexions from fore- and hind limb nerves to cortical cells located in area 3 and in the dorsal part of area 4 (Welt et al. 1967, Asanuma, Stone and Abzug 1968, Wettstein and Handwerker 1970).

Another possibility is that the group I information from hind limb afferents is forwarded to various corticofugal systems originating in area 3a, such as the corticospinal tract (van Crevel and Verhaart 1963, Nyberg-Hansen 1966), the corticorubral tract (Rinvik and Walberg 1963), the corticopontine projection (Brodal 1968), the corticoreticular projection (Brodal, Maršala and Brodal 1967) and the corticothalamic projection (Rinvik 1968 b). It can be assumed that the group I hind limb information to area 3a via mono- or polysynaptic cortical linkages is forwarded to any of these corticofugal systems. The study of Swett and Bourassa (1967 a) indicated that group I forelimb thalamocortical fibres monosynaptically activated pyramidal tract cells. It remains to be seen if group I hind limb thalamocortical axons have similar connexions to corticofugal pathways.

A third possibility is that the group I information from hind limb nerves is utilized in intracortical paths of still unknown function. The group I hind limb input to the postsigmoid cerebral cortex could subserve several control mechanisms, as recent results from physiological studies may suggest. One mechanism would be a feedback control of ascending group I hind limb paths. Such a role is in accordance with the findings of Magni and Oscarsson (1961) that electrical stimulation of the postsigmoid gyrus influenced segmental VSCT cells. Descending influence on DSCT cells has also been demonstrated (Hongo and Okada 1967, Hongo et al. 1967). The cortical position from which effects were elicited by electrical stimulation could well have included the dorsal group I hind limb locus. It is also possible that the group I hind limb loci are involved in descending control of ascending exteroceptive and FRA pathways (Lundberg, Norrsell and Voorhoeve 1963, Gordon and Jukes 1964 b).

The group I hind limb cells of the postsigmoid loci may further participate in cortical mechanisms which depolarize primary afferents (Carpenter, Lundberg and Norrsell 1963, Andersen, Eccles and Sears.

Oscarsson with collaborators have advanced the hypothesis that the forelimb group I projection to area 3a represents a feedback system for adjusting cortical motor output. It is possible that the cortical projection from group I hind limb afferents to area 3a is involved in similar mechanisms. In order to gain a more detailed understanding of how such a feedback system could operate, further studies are required. One step in such an analysis would be to establish whether or not afferents from primary and secondary muscle spindle endings and from Golgi tendon organs influence cells in the group I hind limb loci of the postsigmoid gyrus. If these muscle afferents do influence cells in these loci, it would be of importance to find out whether or not the units are corticofugal. If they are, one would like to know if such cortical cells govern segmental $\alpha$ and $\gamma$ motoneurones.

A study of the afferent and efferent links of cortical group I hind limb cells in the postsigmoid gyrus would have the advantage that the results could be related to the detailed knowledge on spinal mechanisms in which the hind limb group I muscle afferents participate.
VII. GENERAL SUMMARY

This thesis summarizes recent findings of focal potential and unitary studies on the projections to the cat cerebral cortex from fore- and hind limb group I muscle afferents.

Introduction briefly refers to earlier studies on the projection to the postcruciate dimple region (area 3a) in the first sensorimotor cortex from contralateral forelimb group I afferents.

Methodological considerations deal mainly with the problem how to discriminate between axons with different functional properties using electrical stimulation of peripheral muscle, skin and joint nerves.

Section III, Projections to the cerebral cortex from group I forelimb afferents, gives an account of the projections, revealed by focal potentials, from the contralateral group I forelimb afferents to the anterior suprasylvian region, to the lateral ansate region, and to the lateral sigmoid gyrus. The two former projection fields are located in sensory cortices (area 2), the latter in the motor cortex proper (area 4γ). Results are also presented of a unitary analysis of the afferent connexions to cells located in the group I forelimb locus of the anterior suprasylvian region.

The Discussion of the unitary analysis of the group I locus of the anterior suprasylvian region compares the functional properties of these group I cells with group I cells in the postcruciate dimple region, in the thalamus and in the main cuneate nucleus. It is concluded that the observed differences may be explained by the assumption that the afferent paths to the group I cells of the two cortical projection areas are functionally dissimilar.

Section V, Projections to the cerebral cortex from group I hind limb afferents, describes areas in the cerebral cortex which receive projections from electrically activated group I hind limb afferents. Group I hind limb potentials may be recorded in the first sensorimotor cortex (two loci in the postsigmoid gyrus, one on its dorsal and another on its medial surface, mainly in area 3a) and occasionally also in or near the second somatosensory region (area 2). It is concluded that Ia and probably also Ib hind limb afferents excite cells in the postsigmoid gyrus. The course and the relay nuclei of the projection path to the cerebral cortex from group I hind limb afferents is described, with data from focal potential and unitary recordings.

In the Discussion of the group I hind limb projection to the cerebral cortex the relation between the group I hind limb cerebral path and the dorsal spinocerebellar tract is discussed. Some comments are made on the excitatory contributions to the group I hind limb cerebral path from
group II muscle-, cutaneous-, Pacinian and joint afferents. Arguments for and against are given for the tentative conclusion that Ib hind limb afferents project to the cerebral cortex. Functional aspects of the group I hind limb cerebral path are briefly discussed.

VIII. ACKNOWLEDGEMENTS

It is a pleasure to thank my teacher Sven Landgren for enjoyable collaboration in the experimental work performed in Göteborg and Umeå, and also for his unstinted guidance and support in the process of converting laboratory data into articles.

I gratefully acknowledge the time spent in Göteborg, with its rich scientific and friendly atmosphere incited by Anders Lundberg.

My sincere thanks are due to Bo Appelberg and Åke Vallbo for their valuable comments on manuscripts.

I have greatly appreciated working with the excellent laboratory equipment constructed by Erling Eide and Yngve Källström and colleagues in Göteborg, and by Göran Westling, Erland Danielsson and Lennart Näslund in Umeå.

For skilful technical assistance I am indebted to Ewa Lignell, Göteborg, and to Ulla-Britta Olsson and Annebritt Öberg, Umeå.

I thank Berit Lundgren for typing the manuscripts.
IX. REFERENCES

Brodal, P., Marsala, J. and Brodal, A. (1967). The cerebral cortical projection to the lateral reticular nucleus in the cat, with special reference to the sensorimotor cortical area. Brain Res. 6, 252—274.


Jack, J.J.B. and MacLennan, C.R. (1971). The lack of an electrical threshold discrimination between group Ia and group lb fibres in the nerve to the cat peroneus longus muscle. J. Physiol. 212, 35—36 P.


