Sensory-Motor Responses from the Diencephalon

Electrical Stimulation in Man*

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The object of this study was to determine whether or not various parts of the diencephalon could be functionally differentiated by recording the motor and sensory responses elicited during electrical stimulation. The ultimate purpose of this investigation was to determine the value of electrical stimulation in this part of the brain as a technique of localization in stereotaxic surgery.

Technique

One hundred twenty patients with Parkinson's disease were utilized for this study. Only patients who were capable of answering questions, had intelligible speech, and did not require any systemic sedation or analgesia during surgery were selected. Observation of stimulation effects preceded the placement of lesions in the diencephalon as previously described.

Operation. Operations were done with patients in the supine position. One per cent Xylocaine was used for local anesthesia of the scalp. The patients remained awake throughout the procedure and were not premedicated. A frontal burr hole, 3/8 inch in diameter, was placed 1 1/2 cm. from the midline and 7 1/2 to 8 cm. posterior to the glabella. A ventriculogram was performed and utilized for calculating coordinate measurements. These were supplemented with preoperative pneumoencephalograms. A roentgen-ray tube plate distance of 40 inches was used for both lateral and frontal views. The central beam was directed just above the sella in the lateral view and proper corrections were made for distortions.

Coordinate System of Measurement. Horizontal zero consisted of a plane extending from the mid-posterior margin of the anterior commissure to the anterior margin of the posterior commissure. The frontal zero plane was at a point midway between the anterior and posterior commissure at right angles to the horizontal plane. The sagittal zero plane was identified by a vertical line passing through the center of the 3rd ventricle in the frontal projection. For the purposes of this study, the localizations were expressed in terms of the electrode-tip position. However, it must be emphasized that the electrode was oriented in an approximately 40 degree angle with the horizontal zero plane in the sagittal projection.

Electrical Stimulation. Bi-polar electrical stimulation was used. The electrode tip was a bare metal tube 4 to 8 mm. in length and slightly larger than 1 mm. in diameter with the central electrode projecting 1 mm. from its tip. Thus, the total effective stimulation length of the bi-polar electrode was 5 to 9 mm. in length. A Grass square-wave stimulator was used. The sensory and motor responses utilized were those obtained with the least stimulus strength. Parameters of stimulation consisted of 0.5 to 50 volts with the majority ranging from 5 to 10 volts. A 1-msec. pulse applied for a period of 5 secs. duration was used in all stimulations. All points were evaluated in 3 ranges of frequency: (a) 1 to 5/sec., (b) 50 to 100/sec. and (c) 500 to 700/sec. Most points were evaluated with 5/sec., 60/sec., and 700/sec. The intervals between stimulations varied from 30 seconds to several minutes. The majority ranged between 1 to 3 minutes. The sequence of evaluating a given point with various frequencies was random. Most points were evaluated with 10 to 20 stimulation.

Evaluation of Motor and Sensory Responses. The head, neck and extremities were allowed to remain exposed during the period of stimulation. The observations were made with the patient lying in the supine position with arms, legs and neck extended. Motor movements were observed by the operator and his associates. When necessary, observers were assigned to specific parts of the body in order to determine the details of movements. The sensory experiences of the patient were evaluated by asking the patient, "Did you feel anything?" or "what did you feel?" Care was taken not to ask questions which would be suggestive to the patient. However, after a patient related an experience or a sensory response, specific questions were asked in order to elicit further characteristics of that sensory experience. A sensory experience which obviously was associated with an objective movement of a body part was not considered in this analysis as a sensory response. The character of the sensory and motor responses were immediately recorded following each stimulation.

Sagittal Planes for Presentation of Results. Since

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the long axis of the stimulating electrode is oriented in the sagittal plane and sensory representation in the thalamus has a lamellar orientation, it was thought best to present the results in terms of composite sagittal planes. The coordinate system of Schaltenbrand and Bailey was used.26 The stimulated points were grouped in 7 composite sagittal planes representing a fixed mm. distance lateral from the midline, as follows: (1) 4 to 5.9; (2) 6 to 7.9; (3) 8 to 10.4; (4) 10.5 to 12.4; (5) 12.5 to 14.4; (6) 14.5 to 17.4; (7) 17.5 to 22.5. The stereotaxic frontal and horizontal extent were not similar for each of the composite sagittal planes (Table 1).

Method of Analysis. Only those points in the brain which gave positive motor or sensory responses were utilized in this study. A given point which produced a motor or sensory response in more than one body part was credited as representing each of those body parts. To evaluate the representation of a given body part in a particular sagittal plane, the percentage of points from which a positive response was obtained for a given body part was calculated. This was obtained by using the total number of points stimulated within that plane as a divisor. The percentages obtained were then plotted and compared. A comparative percentage frequency was then utilized in order to evaluate the degree of body representation in various sagittal planes.

Results

Motor Responses. Movements usually elicited by low frequencies (5 per sec.) were manifest as jerks occurring in rhythm with the stimulation pulse. The movements occurring with the higher frequencies were usually sustained and tonic in character. The higher frequencies in comparison to the lower ones had a tendency to implicate a greater number of body parts simultaneously.

A motor response elicited from a given body part occasionally implicated a contiguous body part during subsequent stimulations of the same point. In such instances, both body parts were credited as representing that point in the analysis. The threshold for eliciting motor responses was lowest in the more lateral sagittal planes. Once a pattern of motor response was established, it invariably was repeatable with very slight, if any variation.

Character of Movement Response. Eyelid responses were primarily those of elevation. Forced eyelid closure was not observed. Ipsilateral head movements consisted primarily of lateral flexions of the neck with occasional concomitant extension and slight rotation. The contralateral head movements were primarily lateral flexion and rotation. Hand movements consisted of total hand or individual finger displacements. Arm movements were combinations of either flexion,

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**TABLE 1**

**Boundaries of stimulated areas in seven composite sagittal planes of the diencephalon**

<table>
<thead>
<tr>
<th>Composite Sagittal Plane (in mm. from midline)</th>
<th>Frontal Extent</th>
<th>Horizontal Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (4--5.9)</td>
<td>Fp 11 to Fa 5</td>
<td>+2.5 to −5</td>
</tr>
<tr>
<td>2 (6--7.9)</td>
<td>Fp 11 to Fa 2</td>
<td>+ 0 to −5</td>
</tr>
<tr>
<td>3 (8--10.4)</td>
<td>Fp 11 to Fa 2</td>
<td>+ 2 to −11</td>
</tr>
<tr>
<td>4 (10.5--12.4)</td>
<td>Fp 12 to Fa 2</td>
<td>+ 3 to −10</td>
</tr>
<tr>
<td>5 (12.5--14.4)</td>
<td>Fp 12 to Fa 3</td>
<td>+ 3 to −5</td>
</tr>
<tr>
<td>6 (14.5--17.4)</td>
<td>Fp 12 to Fa 2</td>
<td>+ 3 to −6</td>
</tr>
<tr>
<td>7 (17.5--22.5)</td>
<td>Fp 5 to Fa 3</td>
<td>+ 3 to −5</td>
</tr>
</tbody>
</table>

Fp = Frontal Posterior  Fa = Frontal Anterior

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**FIG. 1.** The laterality of motor responses observed in various parts of the body were evaluated in terms of the cumulative percentage of positive points obtained by combining the values of each body part within a given sagittal plane. Refer to Table 1 for the mm. distance, from the midline, represented by each of the 7 sagittal planes. Zero signifies no response.
The motor movements were graphed in terms of laterality for each of eight body parts. In each composite sagittal plane, 1 through 7, the cumulative percentage of positive points for each body part was used. Refer to Table 1 for the mm. distance from the midline, represented by each of the seven sagittal planes. Zero signifies no response.

extension or rotation. Pupil movements were limited to dilation; there was no constriction. The ipsilateral eyeball movements were chiefly medial deviation of the eyeball with an occasional simultaneous downward and rotatory movement. There seldom was upward movement. Contralateral eyeball movements were conjugate. Movements of the foot and leg were complex and did not consist of isolated flexion, extension, inversion, eversion, or rotation.

An evaluation of face movements was not included in this study because it was difficult to differentiate the effects of direct stimulation from those representing an emotional reaction to a sensory experience.

Laterality of Movements. A positive motor response was elicited from 116 points. The body parts evaluated consisted of eyelid, eyeball, pupil, head, hand, arm, foot, and leg. In some instances, a given point only produced a movement response in one body part and in other instances they produced responses in several body parts. The points producing responses in several body parts were most frequently located in the more lateral sagittal plane of the diencephalon. A major transition between ipsilateral and contralateral movements occurred within sagittal plane No. 3 which represents the sagittal composite plane 8 to 10.4 mm. from the midline (Fig. 1). Predominantly ipsilateral responses were obtained from sagittal composites Nos. 1 and 2 which were represented 4 to 7.9 mm. from the midline. A predominance of contralateral movements were primarily elicited from the more lateral sagittal composite planes Nos. 4, 5, 6 and 7. As one progressed from plane No. 3 to No. 7, the accumulated percentages of positive points representing contralateral movements in various body parts progressively increased, with a tremendous jump at
sagittal plane No. 7. This indicated that more body parts were being activated by a given point of stimulus as one progressed laterally from 8 to 22.5 mm. from the midline.

Motor Movement According to Body Part. Fig. 2 shows a detailed analysis of 8 body parts with respect to the percentage frequency of their representation in 7 composite sagittal planes. It should be immediately emphasized that ipsilateral movements were primarily contributed by the eyelid, eyeball, pupil and head. The ipsilateral eyelid movement was the most strongly represented. Between sagittal planes Nos. 3 and 4 there was an abrupt decreased representation. In the remaining more lateral planes, contralateral eyelid movement became more predominant. Movement of the ipsilateral eyelid usually involved elevation and not closure. Dilation of the ipsilateral pupil was predominantly represented in plane No. 2, which is 6 to 7.9 mm. from the midline. Contralateral pupillary dilation began to appear in plane No. 3 and remained as a relatively constant response throughout stimulation of the lateral portion of the diencephalon. Bilateral pupillary dilation was often observed with changes in emotional states and so was not plotted. The eyeball of the ipsilateral eye moved independently of that in the contralateral eye in plane No. 1. The movement was primarily a medial deviation of the eyeball. At times this was accompanied by a simultaneous downward and rotatory type of displacement. Starting at sagittal composite plane No. 2, conjugate eye deviation to the contralateral side occurred with greater frequency as one progressed laterally; the greatest number of points were in the 6th and 7th planes. The hand and arm were not represented in any of the points stimulated in sagittal composite planes Nos. 1 and 2. However, both the arm and hand showed increased point representation as the stimulation progressed laterally from planes Nos. 3 to 7. As stimulation progressed from medial to lateral, the slope of the curve for arm representation was greater than that for hand, which suggests that diencephalic representation for the hand is more medially concentrated than that for the arm. Foot and leg responses were conspicuously absent in the first 3 composite sagittal planes (5 to 10.4 mm. from the midline). Both the foot and leg responses started to appear in plane No. 4 and increased progressively as stimulation moved laterally. However, the rate of increased point representation for the leg as one progressed laterally was much greater than that for the foot. Just as in the hand-arm relationship, this implied that the diencephalic foot representation extends more medially than that for the leg.

Sensory Responses According to Body Part. Sensations in the face included those dealing with the eye, ear, nose, mouth, tongue, throat and neck. The percentage frequency of sensory responses according to body part, irrespective of the modality of the response, were tabulated according to composite sagittal planes (Table 2). A graphic presentation of their relative degrees of presentation in each composite sagittal plane was constructed (Fig. 3). We noted that as the stimulation progressed from medial to lateral in the various planes there was a cephalo-caudal orientation of the body parts.

Face and hand sensory representations were greatest in composite plane No. 2, which represents points stimulated within 6 to 7.9 mm. from the midline. As stimulation progressed laterally, face representation dimin-

### Table 2

<table>
<thead>
<tr>
<th>Composite Sagittal Plane Stimulated</th>
<th>Points</th>
<th>Face</th>
<th>Head</th>
<th>Body</th>
<th>Chest</th>
<th>Stomach</th>
<th>Arm</th>
<th>Hand</th>
<th>Leg</th>
<th>Foot</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>50%</td>
<td>33%</td>
<td>33%</td>
<td>33%</td>
<td>17%</td>
<td>33%</td>
<td>21%</td>
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<td>12%</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>86%</td>
<td>36%</td>
<td>39%</td>
<td>33%</td>
<td>48%</td>
<td>57%</td>
<td>48%</td>
<td>48%</td>
<td>39%</td>
</tr>
<tr>
<td>3</td>
<td>43</td>
<td>42%</td>
<td>25%</td>
<td>29%</td>
<td>29%</td>
<td>2%</td>
<td>51%</td>
<td>37%</td>
<td>37%</td>
<td>24%</td>
</tr>
<tr>
<td>4</td>
<td>34</td>
<td>58%</td>
<td>18%</td>
<td>32%</td>
<td>32%</td>
<td>3%</td>
<td>59%</td>
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<td>29%</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>62%</td>
<td>31%</td>
<td>69%</td>
<td>69%</td>
<td>8%</td>
<td>38%</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>75%</td>
<td>33%</td>
<td>50%</td>
<td>50%</td>
<td>17%</td>
<td>58%</td>
<td>8%</td>
<td>8%</td>
<td>42%</td>
</tr>
</tbody>
</table>
ished abruptly in plane No. 3 and then progressively increased, whereas the hand was minimally represented in the 5th and 6th planes. The greatest representation for the arm was in the 4th composite plane. It became markedly reduced in the 5th and then showed an increased representation in the 6th plane.

The body was represented in all planes but the conspicuously greatest representation was in the 5th sagittal plane which is 12.5 to 14.4 mm. from the midline. The leg also was represented at its maximum in this plane. Sensations in the foot were predominantly represented in the 4th plane. The greatest representation for the foot was in a sagittal plane medial to that for the greatest representation for the leg just as the hand was medial to the plane of greatest representation for the arm. The foot and leg were not represented in the 1st sagittal plane nor was the foot represented in the 2nd plane.

Sensation in the stomach started in the 3rd composite plane and progressively increased to the 6th. The 6th sagittal plane shows a relatively strong representation for all the body parts considered, except the hand. Since this plane is 14.5 to 17.4 mm. lateral to the midline, the probability is that compact fiber systems projecting to the sensory cortex and representing a variety of body parts were activated.

Character of Sensory Responses. The experiences which the patients reported were primarily characterized as sensations of “electricity,” shock, tingling and movement. Table 3 contains the relative frequency of these various sensory responses according to the percentage of positive points found in each of the composite planes. “Electricity”
and shock were combined since they probably represented a similar experience. It will be immediately observed that the electricity-shock sensation occurred more frequently than did tingling. Movement-sensation was more frequent than either of the others. A sensation such as, "I feel a shock running down my arm," was tabulated under both categories, electricity-shock and movement sensation or "cinesthesia."* If the patient merely stated, "I feel electricity (or shock) in my left arm," it was tabulated under the category of electricity-shock. In other words, movement-sensation which was obviously associated with an overt motor response in the body part under question was not tabulated as a sensory experience. There was no apparent correlation in the frequency of response of movement-sensation and electricity-shock or tingling. Preliminary analysis of movement-sensation in terms of the various sagittal planes showed approximately equal frequency of representation between them. However, a more detailed analysis of the movement-sensation in terms of various body parts in the various planes revealed significant differences between the lower and upper extremities (Fig. 4). For example, the leg and foot contained no representation of movement-sensation in any plane except the 4th and this was very minimal for the foot. The face, body, head, and arm showed the greatest representation for movement-sensation. It is of interest to note that the hand which had a relatively extensive sensory representation especially in the 2nd plane, present very little movement-sensation in that plane. Other modalities of sensation which the patients experienced included touch, pain, temperature, vibration and position sense. The electricity, shock and tingling sensation in most instances were not disagreeable unless supra-threshold stimuli were used. Stimulations located medially were more disagreeable than those located laterally.

Examples of movement sensations (cinesthesia) are: Pt. 174: "Felt like something going up my arm, kind of up my elbow. It seemed like it wanted to travel up my arm to my elbow but then it stops." Pt. 172: "Feels like electricity going through my whole body." Pt. 209: "Felt tears coming on, left side under my eye." Pt. 216: "Something going through my right arm and lower part of my body and both legs." Pt. 227: "Crazy feeling all through my system; I saw hands." "Crazy feeling like going round and round." Pt. 177: "Something going funny, I feel it, I smell it and I see it. Everything funny in the room, jumping like grasshoppers." Pt. 116: "Just a sensation going through my body, like when you are frightened." Pt. 138: "I had a funny feeling like I was going to go somewhere." Pt. 77: "It felt like a pressure

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* See Addendum

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**TABLE 3**

<table>
<thead>
<tr>
<th>Composite Sagittal Plane Stimulated</th>
<th>Stimulated Points</th>
<th>&quot;Electricity&quot; or Shock %</th>
<th>Tingling %</th>
<th>Movement Sensation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>64</td>
<td>29</td>
<td>79</td>
</tr>
<tr>
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<td>43</td>
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<td>63</td>
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</tr>
<tr>
<td>5</td>
<td>13</td>
<td>54</td>
<td>15</td>
<td>85</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>75</td>
<td>8</td>
<td>100</td>
</tr>
</tbody>
</table>

**Fig. 4.** Frontal view of "sensation of movement" in body parts represented in the diencephalon. The height of the bars corresponds to the percentage frequency of positive points for a given body part within a given composite sagittal plane. The scale of reference is the same throughout. Blank space signifies no response in the plane indicated for the given body part. Note that "sensation of movement" in the hand, foot and leg is conspicuously minimal and does not parallel the degree of representation for the broader spectrum of sensory responses demonstrated in Fig. 3.
circulating through my right arm.” Pt. 55: “Something flashing through whole face.” Pt. 48: “Upper teeth felt as if they were being pulled out. Not strong, but something pulling down.” Pt. 46: “Seems like my teeth are separating.” “The tongue in the air as if it were folding up.”

Discussion

Problems which may have influenced the results. Since the thalamus possesses a lamellar organization of sensory representation, the cephalic end of the body being most medial and the caudal end most lateral, the diencephalon was arbitrarily divided into 7 composite sagittal planes of different widths. The lateral extent of each composite sagittal plane varied from 1.9 mm. to 4 mm. in width in order to allow for a greater variability of anatomic relationships as stimulation proceeded laterally from the midline. The maximum distances beyond the stimulating surface of the electrode for activation within a given plane thus varied from 1–3 mm. The frontal and horizontal limits of each composite plane were not similar. This was not thought to be critical since the greatest extent of the activated tissue was in the sagittal plane which is the major orientation of the lamellar organization. The points stimulated in the 1st and 7th composite planes were relatively few.

Anatomic variability between brains of various individuals has been previously stressed and well documented. Third ventricular size was found to vary in Parkinson patients. This also implies variation in spatial relationships of the surrounding diencephalic structures.

Sensory responses reported by the patients were obviously dependent upon the education and past experiences of the patients whose ages ranged from 31 to 79 years. Analysis of the sensory responses was based on terminology used in common everyday language and simple sentence structure.

Electrical stimulation with a relatively large area of exposed electrode (5–9 mm. length) and varied stimulation frequencies obviously activated large and different neuronal populations, both fiber and cellular. The purpose for this method of tissue activation was to evaluate the varied functions of the wide range of neuronal populations or elements lying within and coursing through that part of the brain which would subsequently be destroyed.

Sensory-motor representation of body parts. In spite of the problems discussed above, it was possible to demonstrate abrupt differences and definite trends in the representation of body parts between the various sagittal planes for both the sensory and motor responses. Reports by others indicate more or less similar observations although no detailed topographical mappings have been produced. Sensory representation of body parts in the diencephalon appeared to correlate rather favorably with the findings reported for the thalamus in animals. The body parts were oriented in the mediolateral distribution with the cephalic end being more medial and the caudal end lateral. The caudal end occupied a relatively narrower sagittal band of tissue than the more cephalic structures. The distal portions of the extremities were a little more medially represented than the proximal portions. Contralateral sensory representation appeared to predominate. No exclusively ipsilateral sensory responses were elicited. This observation was also made by others. However, responses tabulated as representing the body as a whole may actually represent a mixture of ipsilateral and contralateral sensory elements which were simultaneously activated. In contrast, ipsilateral motor responses were present and were mainly elicited from the medially located sagittal planes. Ipsilateral motor responses primarily involved the cervical, extraocular, and pupillary musculature; contralateral motor responses were from the more lateral planes.

Character of the sensory responses. Just as in cortical stimulation, the sensations of electricity, shock and tingling were relatively common. However, a subjective sensation of movement was a very frequent component of the sensory responses. This type of sensation apparently is not a frequent component of responses obtained from stimulation of the sensory motor cortex or temporal lobe structures. The diencephalon thus appears to play a unique role in the manifestation of this physiologic function. Since this component of sensation implicates “time” the observation suggests that the dienceph-
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al is intimately involved in the fourth dimension. A similar suggestion was reached in considering normal thalamic integration of sensory input. Several questions may be asked relative to the mechanisms responsible for the subjective sensation of movement during electrical stimulation of the diencephalon. Is it due to activation of proprioceptive systems, a sequential activation (in time) of sensory neurons representing different body parts, or a sequential subclinical activation of central and peripheral motor elements with secondary proprioceptive feedback? It is reasonable to believe that all 3 of these mechanisms in addition to others, presently unknown, must be involved in varying degrees. This important component of sensation deserves further investigation.32

Sensory motor responses and stereotaxic localization. Although a definite organization of body representation for both sensory and motor responses were found in the human diencephalon, there was extensive overlapping of various body parts. It should be noted that overlapping also was found in thalamic sensory maps obtained by strychnine applied to the thalamus and potentials evoked from stimulation of peripheral organs.8,9,10,20,23 The overlapping organization, whether real or an artifact of technique, greatly limits the use of these observations for stereotaxic localization in the human diencephalon. This is especially true when anatomic localization is attempted from sensory-motor responses obtained at a single site. In order to facilitate localization 2 or more sites must be compared. The greater the number of sites being compared, the greater is the relative probability of localization within a given patient.

Summary

1. In 120 patients with Parkinson’s disease the diencephalon was electrically stimulated and the motor and sensory responses recorded.

2. For purposes of analysis the diencephalon was divided into 7 composite sagittal planes.

3. The motor and sensory responses were analyzed in terms of positive points representing various body parts within each of the sagittal planes. Percentage frequencies of the positive points were used to make comparisons between various planes.

4. Ipsilateral motor movements were elicited in the medial sagittal planes and contralateral motor movements from the more lateral planes.

5. The ipsilateral motor movements were predominantly confined to the eyelid, neck, pupil, and the ipsilateral eyeball.

6. Sensory representation of the body parts were oriented in a mediolateral direction with the more cephalic structures being medial and caudal structures lateral.

7. The character of the sensory responses most frequently encountered were electricity, shock, tingling, and movement-sensation.

8. Movement-sensation termed “cinesesthesia” was the most frequent component of the sensory responses.

9. Sensory and motor responses elicited by electrical stimulation of the diencephalon cannot be used as a precise technique of localization in stereotaxic surgery.

References


Addendum

Cinesthesia. The author wishes to acknowledge a discussion with Dr. Lawrence Stark which led to the creation of a new word whose Greek derivation suggests a moving sensation or one whose location is not fixed.