The Midbrain and Motor Integration

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'The motor individual is driven from two sources. The world around it and its own inner world within. Its activity is also partly operated by nervous activity arising spontaneously within the nervous centres themselves' (Sherrington 1940, p 181).

In a remarkable tribute to Sir Charles Sherrington, his former collaborator and associate, Professor E G T Liddell (1960), has drawn an entertaining and vivid picture of the painfully slow development of knowledge of the physiology of the nervous system up to the time Sherrington began his life work. His outstanding contribution was the unravelling of the patterns of spinal reflexes and their interaction. Sherrington also made remarkable contributions to the study of the management of spinal reflexes by the brain-stem mechanisms, enough to show the complexity and lability of these in contrast to the more readily identifiable spinal level of management. The clinician must of necessity deal with perturbation of nervous function at all levels and, in his gropings for better understanding of derangement of hemisphere and brain-stem function, is still in many respects facing the same confusion of ideas of nervous action at these levels that characterized the pre-Sherrington ideas of spinal reflexes.

As Professor Liddell has so well portrayed in his memoir, the development of knowledge of function had to be preceded by analysis of structure. Often, however, a plausible but wrong idea, derived from some purely anatomical premises, had for a very long time delayed the true appreciation of the nature of function. This last difficulty has plagued the investigation of cerebral physiology, where anatomical connexions, or their equivalent stimulated effects, have for too long served as explanation for physiological function. The physiologist on the other hand finds in the brain a plasticity of functional performance that makes him unwilling to make absolute identification of structure and function. In addition it often appears that at this level the whole is not necessarily just the sum of all the parts, a haunting doubt that pervades 'Man on His Nature' (Sherrington 1940).

Decerebrate Rigidity

Though his few contributions to the physiology of the brain are outstanding, Sherrington did not become embroiled in the controversies over cerebral localization and function: Yet the discovery of decerebrate rigidity (Sherrington 1897a, b) and its systematic analysis is a great landmark in the development of neurology, for it is the classic example of release of nervous activity. Magendie (1823) had in fact described accurately the decerebrate phenomenon in the rabbit and its abolition by pontine section. Löwenthal & Horsley (1897) had evidently observed the 'cataleptoid state' independently of Sherrington about the same time. But it was Sherrington who performed the seemingly impossible feat of demonstrating that the extensor spasm arose in each muscle concerned, with the final analysis of the stretch reflex by Liddell & Sherrington (1924). We predict that, just as Bell's discovery of the afferent and efferent roots was the most significant single advance in all spinal physiology, the discovery of decerebrate rigidity will in future years mark the point at which understanding of the mechanism of the brain really began. For Sherrington it provided a background of activity on which to test and enlarge his views of the nature of inhibition, but in addition it was the starting point for the exploration of righting reflexes by Magnus (1924) and by Rademaker (1926) and more recently of the nature of cerebellar effects so brilliantly exploited by Stella et al. (1955), Moruzzi & Pompeiano (1957) and Sprague & Chambers (1953).

Of the many remarkable features of decerebrate rigidity the foremost is its immediate and invariable appearance following transection be-
tween the intercollicular level and upper pons. There is no phase of initial shock. Sherrington (1898) observed that the exaggerated posture was not abolished by section of the dorsal columns of the spinal cord, or by ablation of the cerebellum, or by section of the VIII nerves. It was abolished in any limb by deafferenting that limb. The stretch reflex, however, is a spinal reflex (Denny-Brown & Liddell 1927), and there still remained the question as to the source of the heightening effect. This question is still not finally settled. In part there is facilitation of some spinal stretch reflexes by the exclusion of those of other segments. Thus transection of the spinal cord behind the cervical enlargement heightens the rigidity in the forelimbs (the Schiff-Sherrington phenomenon). There are also other interactions, for if the cerebellum is removed the rigidity again appears in the deafferented limb, as Stella and his associates (1955) have shown. This effect is in part due to a restraining effect of the anterior vermis on the labyrinthine system through the fastigial nuclei. The extensor spasm then still seems to follow the pattern of the original decerebrate rigidity, but with the addition of more neck extension, which in turn frequently sets up a neck reflex causing extension of the forelimbs. The stretch reflex, however, is subdued, and it is now the alpha neurons that are hyperexcitable.

Such observations only inform us that by such manoeuvres it is possible to secure an exaggerated tonic labyrinthine and neck reflex. Decerebrate rigidity itself is not defined. Section of one VIII nerve or destruction of Deiter's nucleus on one side abolishes decerebrate rigidity on that side, but the effect is from the other labyrinth, destruction of which restores bilateral rigidity. The essential anti-gravity posture remains in an intercollicular preparation with the VIII nerves and dorsal columns sectioned.

Hemisection of the Spinal Cord
Following hemisection of the spinal cord in the high cervical region the cat and monkey make an astonishing degree of recovery from the paralysis of the limbs on the side of the lesion. As Mettler (1944) has well described in the monkey, it may be difficult for the casual observer to distinguish the side of the lesion from the behaviour of the animal after some months. In unpublished work with another objective in 1949 with Drs T Twitchell and L Saenz-Arroyo on cervical hemisection in the cat, we found in 3 animals that later decerebration, two to ten weeks after hemisection of the spinal cord at C3 level, produced decerebrate rigidity of comparable intensity in all four limbs. In two other animals with slightly lower levels of cervical hemisection the rigidity was not quite as well developed in the ipsilateral forelimb until an interval of at least three weeks had elapsed. With Dr Twitchell and, later, Dr C W Watson, we found the same phenomenon in two macaque monkeys with high cervical (C3–C5) hemisection. In both cat and monkey it was also found that prior to decerebration the animals were unable to right themselves if they lay on the side opposite the hemisection but could do so rapidly and effectively if they lay on the side of the lesion (Fig 1c). After two to three weeks they learned to roll, or to claw with their uppermost limb if lying on the opposite side. Primary righting of the head continued to occur only when lying on the side of the lesion as long as three months after hemisection. After the first three weeks the ipsilateral arm could support the animal when it was tilted to that side, and with this reaction there developed the ability to use the hand for prehension (Fig 1a, b).

This finding shows that the descending pathway that mediates decerebrate rigidity is plastic, and bilateral. In the lower limbs it adjusts to thoracic or high lumbar hemisection within ten days. Like the descending pathway for respiration it can cross in the spinal cord below any level of hemisection and in this respect resembles a network rather than a tract. In this phenomenon we sense the operation of a one-ness of fundamental nervous activity that sets it apart from the unilateral dependence of all the adjustments of the organism to the external world. On the other hand the ascending pathway for most if not all the body contact righting reaction is crossed, and
reaches the other side of the spinal cord in four to six segments. This is the reason that righting is preserved on the side of hemisection. It is an acquired modification of the basic mechanism.

The Reactions Released by Decerebration
Rademaker's (1926) study of the structures involved in acute midbrain section showed that in the rabbit and cat the crucial structure lay in the ventral half of the midbrain, and was vulnerable to midline section in that region. He identified the red nuclei and Forel's decussation as the essential component, destruction of which abolished phasic labyrinthine and body-on-body righting, releasing decerebrate rigidity.

Subsequent investigations have shown that the situation is more complex. It has been most difficult to keep decerebrate preparations alive for more than a few days. The experience of Bazett & Penfield (1922), with longest survivals of 18, 22 and 23 days, has been enlarged by Bard & Macht (1958) with preservation of hypothalamus above the lesion, which enabled much longer periods of observation. Their pontine transections were observed for 35 and 39 days, low mesencephalic sections for 30 and 56 days, and high mesencephalic transections for 31 and 154 days. Decerebrate rigidity remained intense for only a few days, then lessened steadily with the appearance of flexion and crossed extension reflexes, and stepping movements. Tonic neck and labyrinthine responses appeared. Some righting of the head occurred in cats with pontine section, and the uppermost limbs flexed, but the animals could not right, and if propped up, could not stand. After two weeks the shoulders could be righted, but not the hindquarters. Cats with low (inferior colliculus) mesencephalic section could right themselves to a crouching posture, and if stimulated could walk in crouched posture. With high (precocious) level of midbrain section the animal could sit, stand, walk spontaneously, and climb. There were even weak hopping reactions, and coarse proprioceptive placing. In that state the rigidity reappeared only if the cat was suspended in air, or in any leg allowed to hang over the edge of a table. When any of the animals, pontine or mesencephalic, lay on one side the upper limbs flexed and the under limbs extended, 'a reflex figure basic to the act of righting' (Bard & Macht 1958). I have some observations of survival of decerebrate monkeys to amplify these conclusions. They also show that the first and most important modification of decerebrate rigidity that occurs in prolonged survival is the appearance of the positive supporting reaction and related movements of progression.

Chronic Low Decerebration in the Monkey
In a mature female macaque monkey (lab. no. BG 27) a large lesion of the caudal dorsal two-thirds of the midbrain was produced by direct section, leaving only the basis pedunculi intact (Fig 2). The colliculi, aqueduct, central grey matter and caudal mesencephalic tegmentum were removed, leaving intact the subthalamic tegmentum and red nuclei, with the hemispheres above, and the pontine tegmentum below. On the day following operation the animal lay on one side with extreme extension of all limbs, tail and neck. The fingers and toes were loose, the wrist and ankles weakly resistant. On the second and succeeding days the rigidity greatly lessened, and if the animal was laid on its back the forelimbs flexed, then the hind-limbs.

By the sixth day, a positive supporting reaction appeared, so that passive dorsiflexion of the wrist or ankle led to immediate stiffening of the whole of the stimulated limb. When the animal lay on one side the upper limbs occasionally showed a flexed posture, and with it the traction response (active flexion) and closure of the hand or foot in response to a contact stimulus to the palm or sole. No movement of the contact stimulus was necessary, differentiating the reaction from the grasp reflex (which is also not dependent on posture). Passive extension of digits still caused extension of the limb. By the ninth day a strong passive dorsiflexion of any hand or foot led to extension of all the limbs and dorsiflexion of the neck. This spread of reflex effect occurred first to the diagonally opposite limb, and at times led to a reciprocal alternating progressive movement of flexion and extension in all limbs. In the following days an extensor thrust and gallop progression could be induced in this way. There was never any righting, placing or hopping, or lateral tilt reaction, so that the animal had a fixed doll-like appearance. The animal had exhibited periodic respiration throughout, and could not swallow. It was sacrificed on the sixteenth day.

This animal showed a complete absence of any spontaneous movement in spite of integrity of the

Fig 2 Sections from a chronic decerebrate monkey showing the extent of removal of dorsal midbrain, most complete at the level of the posterior colliculus (b) and extending under the superior colliculus (A), with some patchy damage to cerebellar white matter (C)
pyramidal system. The state of decerebrate rigidity underwent changes similar to those described in Bard & Macht's cats. The preservation of the corticospinal system avoided the long period of depression associated with section of this tract, and allowed the rapid development of elementary contact and traction reactions, and of the elements of righting reactions in the hands and feet in response to asymmetrical body contact. These are but details of the 'righting reflex figure' that Bard & Macht found in their chronic pontine cats. The primary change is an enhancement of gamma discharge, as Eldred et al. (1953) have demonstrated. It will be noted that the resulting reactions are not entirely proprioceptive. It is apparent that lack of activity in the hands and feet of the acutely decerebrate animal is due to the profound shock that follows the associated pyramidal section. The traction reaction, by which the limb flexes in response to passive extension of the fingers, can usually be demonstrated in the monkey immediately after complete precollicular section of the midbrain, but the contact closing reaction is then absent. If a monkey is decerebrated by complete intercollicular section following removal of the precentral gyrus some weeks earlier the traction reaction then also appears, but we have not succeeded in securing long survivals in this state.

In another chronic experiment I used the avoidance of pyramidal shock by previous ablation of precentral cortex to show that the type of decerebrate rigidity related to loss of the cerebellar vermis is essentially the same disturbance of motor function as that produced by the classical intercollicular lesion. The description of recovery of movement in this animal follows.

**Chronic Lesion of Cerebellar Vermis and Tectum after Bilateral Corticospinal Lesion**

The precentral gyrus was removed on both sides in a young but mature male macaque monkey five months before induction of a dorsal midbrain lesion including the inferior colliculus and the caudal half of the superior colliculus, with all the underlying central grey and aqueduct, leaving III nerve nuclei, posterior longitudinal bundle and central tegmental tracts intact (Fig 3). In addition, clipping the superior cerebellar arteries resulted in a clear-cut infarction of all the anterior vermis (Fig 3A) without damage to cerebellar nuclei or superior peduncles. In the five months following the cortical operations, the animal had recovered the ability to grasp clumsily with all

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**Fig 3** Representative sections of monkey BG 24, showing infarction of vermis in A, the maximal extent of removal of tectum at intercollicular level in B, and sparing of the rostral part of superior colliculus in C. **Survival 34 days**

**Fig 4** The monkey BG 24 showing, in A the general extension one day after operation, and in B the effect of passive dorsiflexion of the right ankle. In C is shown the extension on being held suspended ten days after operation, and in D the absence of abduction in tilting sideways. In E is shown the grasp of the hand when the palm is touched, in F the extension and positive supporting reaction when a flat surface was the stimulus.
limbs by vision, could use thumb and forefinger to pick at objects, had excellent visual placing, slow contact placing, and very slight spasticity in all limbs. Righting was rapid and effective, and the responses of the limbs we call the 'tilt reactions', flexion on tilting backward and abduction on tilting sideways, and to hopping, were excellent. There were strong positive supporting and traction reactions, and a rather stiff awkward gait, without the over-adduction that had been present for the first month.

After the cerebellar and tectal lesion there was intense decerebrate rigidity interrupted by bursts of running movements in all four limbs. The fingers and toes were stiffly extended (Fig 4a), but became flexed if the animal lay flat on the back, or if contact was applied to the palm of hand or sole of foot (Fig 4b). He showed a strong traction reaction. The animal swallowed well if liquid was placed in the mouth. The eyes showed roving movements, with reactive pupils, but with no evidence of fixation or visual reaction. By the third day the postural reactions in the limbs became very brisk and facile. If the animal was suspended in air the limbs extended (Fig 4c). The animal attempted righting by flexing the upper limbs and reaching across the body (Fig 4d). There was at this time no righting of the head, no compensatory eye movement, and no lateral tilt or placing reaction. A touch to the palm of the hand induced closure (Fig 4e) whereas contact with a flat surface that extended the fingers passively induced a strong supporting reaction (Fig 4f). Over-adduction of the limbs was prominent. The forward tilt reaction now began with only slight change in body contact, and without alteration of the posture of the head (Fig 5a), and proceeded all the way from fully flexed to fully extended posture. A sudden dorsiflexion of wrist or ankle could induce progression movement in the diagonally opposite limb (Fig 5a). Righting of the head from lying on the right side appeared on the fourth day, and at this point the extensor rigidity when lying disappeared. There was still no reaction to tilt, and no righting in a free fall. On the sixth day he could right himself from either side by rotating the trunk and pushing up with opposite arm and leg. He was completely expressionless and mute, but now could recognize his bowl and reach for it with the left arm, and look to a moving object in the left visual field. On the tenth day he could abduct the limbs in order to support himself when tilted, and could right by abducting the under arm. A coarse tremor of the trunk of cerebellar type appeared in sitting posture. By the seventeenth day the ability to abduct the right limbs was greatly improved, and the adductor spasm had disappeared in all limbs. By the thirtieth day the tilt reactions were extremely brisk. The animal could now reach out to objects in either visual field, grasp a large object, and carry it to his mouth. In doing so he frequently exhibited a violent cerebellar tremor. Some slow righting in a free fall had now also appeared. On the thirtieth day both cuneate nuclei were destroyed by direct vision. In the following three days no change could be detected, and in particular the body contact righting and hand contact grasping were unchanged.

This experiment demonstrated the extraordinary decerebrate posture related to loss of anterior vermis if compensation for loss of corticospinal function had been first allowed to occur. As head righting returned, the extensor rigidity of the neck disappeared; as the positive supporting and contact traction reactions returned, decerebrate rigidity disappeared; and as the lateral tilt reactions returned, adductor rigidity disappeared. The decerebrate state in this animal is the alpha rigidity described by Eldred et al. (1953), long known as the 'anæmic' decerebration of Pollock & Davis (1930).

It is clear that decerebrate rigidity, whether of the classical intercollicular type, with hyperactivity of gamma neurons, and consequently exaggerated stretch reflexes, or of the cerebellar type with enhanced alpha discharge of labyrinthine origin, is essentially an unstable condition. Other reactions soon reappear to modify the extensor rigidity, and in each case the positive supporting reaction and diagonal progression are the first modifications, soon to be followed by a negative traction-flexion reaction. At the same time the rigidity becomes plastic,
suggesting both gamma and alpha activity. In both states diffuse contact effects ultimately reappear in the form of fragments of body-on-body righting reactions, with local contact reactions in the hand and foot. I therefore find no fundamental difference between the behaviour of the so-called gamma type of decerebrate and the alpha type, and our problem resolves itself into that of the nature of the general reaction that is released, and the structure that is responsible for it.

The Essential Structure
Magoun & Rhines (1947) showed that the reticular substance of the upper pontine tegmentum has a predominantly excitatory effect on spinal neurons, chiefly but not exclusively on the gamma system. This is exerted mainly through the crossed reticulospinal tract. The non-specific nature of the pathway is shown by our hemisection experiments. The mammalian reticular system is extremely complex, and our best information comes from the studies of Coghill (1929) and Herrick (1948) on the less elaborate organization of salamanders. Coghill showed in these creatures that the pattern of progression by diagonal limb movement appeared as a whole, long before isolated fragments of flexion of limbs to local stimulation were obtainable. It also appears before reaction to stimulation in fishes and birds.

Detwiler (1946) found that in young larval amphibians swimming movements were perfectly executed after transection below the auditory vesicle, controlled by the lower medulla and spinal cord. Subsequent to a later stage of development sustained motor activity, including swimming, was found to fail rapidly if the influence of the midbrain was eliminated. ‘The midbrain evidently supplies a factor essential for maintenance of motor efficiency’ (Herrick 1948, p 63). Hooker (1944) found that in a comparable stage of development of the human foetus the mechanical marionette-like performance changed to the more graceful fluid movements seen in the newborn. The comparative anatomists attribute such co-ordinated behaviour to the effect of the neuropil, the mass of small cells with richly branched processes that pervade the tegmentum. In this primitive network develop the patterns of connexions that reflect the inherited evolutionary motor sequence of progression and other simple behavioural patterns. A spinal reflex such as a flexion reflex is a fragment of a larger context. ‘Such a reflex movement, taken by itself, is equivocal of purpose; it can enter as a fraction into various reflex acts of wholly different purpose. It is a fragment of an act, not an act’ (Sherrington 1940, p 211).

The importance of anatomical determinants of behavioural reflex pattern became apparent when the finer analysis of synaptic interaction in the spinal reflexes by Sherrington revealed that the outcome was dependent upon the number of synaptic boutons provided for any given motor neuron by a particular pathway. The reflex could be graded, modified, inhibited, but the pattern of transmission was pre-ordained by the anatomical factor of bouton density. It therefore should not be difficult to proceed to the assumption that the most elementary nervous structure, universally present throughout the vertebrate series, the reticular formation of the brain-stem and spinal cord, should carry this inbuilt pattern of activity. Ludwig Edinger (1908) not only emphasized the importance of the reticular system but pointed out its tectal mesencephalic extension and the elementary afferent and efferent pathways connected with it. The secondary sensory pathway of Edinger is the spinothalamic tract of mammals. Its tactile division, the ventral spinothalamic tract, is by no means insignificant even in primates, and loses most of its fibres as it ascends through pontine and mesencephalic tegmentum. It provides a substantial contribution of afferent fibres to the colliculi as well as to the mesencephalic reticulum. The down-going tecto- and reticulo-spinal pathways are both crossed and uncrossed. Our hemisection experiments demonstrate that the control of spinal segments can be exerted by either side alone.

Though the results of chronic survival experiments do not substantiate the particular function assigned to the red nucleus by Rademaker (1926), his acute experiments clearly demonstrated that there is a most important physiological transition at the level of this structure. In this transition the pyramidal tract, the substantia nigra, the brachium conjunctivum, the superior longitudinal fasciculus and the colliculi were specifically excluded by Rademaker’s experiments. It is more difficult to implicate any particular part of the all-pervading mesencephalic reticulum, the felt-work of nerve fibres that form the capsule of the red nucleus, and the neuropil of elementary neurons that form the central grey. Fragments of progression and righting reflexes are present in the spinal segments. Increasing extent of the pontine and mesencephalic tegmentum can be said only to improve the regularity and initiation of these reactions, for which they provide the total pattern. The most critical change occurs in the immediately precollicular reticulum.

The Effect of Precollicular Section
In the clinic, as a result of displacements of the brain at the opening of the tentorium, states of decerebrate rigidity of all four limbs occur in which the eyes turn upward, the head retracts
and all limbs are not only stiffly extended but also internally rotated, with strongly clasped hands. This condition does not occur as a result of transection of the midbrain in animals. In man it is occasionally seen as a one-sided reaction, also related to tumour of the brain-stem as in the case reported by Cathala (1922). The internal rotation and extension of the limbs on one side is then associated with deviation of the head and eyes up and back to the opposite side. The origin of this curious posture has been a mystery, though the rotation of the limbs is of importance in relation to better understanding of the rotary tremors of the limbs that occur in so-called "midbrain tremor" and hemiballismus. Hess (1949) found that if one interstitial nucleus is destroyed the overaction of the other is such as to lead to a torsion of the head and eyes. In the monkey we have succeeded in producing this dystonic torsion of the head and limbs only by a lesion that lay between the interstitial nucleus and red nucleus (Fig 6A). When the condition is unilateral and severe the animal rolls over and over in a corkscrew spiral of progression (Fig 6B). The reaction is most complex and I shall not discuss it further here except to say that the level of disordered function in this type of decerebrate state is pretectal and not mesencephalic. In man the bilateral decerebrate attitude of head retraction with internal rotation of limbs arises because the pretectal region is displaced downwards by large brain lesions into the tentorial opening, so that the level of impaction is actually just above the midbrain. It is a disorder of labyrinthine co-ordination of righting of head and eyes with secondary limb effects.

Overaction of labyrinthine and body contact righting of the head, in addition to decerebrate rigidity, thus requires a level of section rostral to the red nucleus in the monkey, severing its connexion with the remainder of subthalamus. The tonic labyrinthine reactions mediated by the pontine reticulum are orientated to gravity, whereas the phasic and tonic pretectal responses are orientated to the longitudinal axis of the body. It has not yet been possible to separate the body-on-head and labyrinth-on-head mechanisms at this level. Both control the distribution of body posture by connexions with the reticulum in the region of the red nucleus. It is the destruction of this mechanism that results in the release of the gamma type rigidity that is characteristic of intercollicular decerebration.

Sherrington found that the dorsal columns were not of importance in decerebrate rigidity, though one might have expected this contribution of the proprioceptive system to play some very essential part. He did not discuss this striking discrepancy. It will be remembered, however, that Brouwer (1927) showed that the dorsal columns were a relatively late development in the mammalia. They are important for the instinctive grasp reaction and other types of orientated cortical contact reactions that affect the motor system at a higher level, which we have recently discussed in relation to the function of the basal ganglia (Denny-Brown 1960).

Decerebrate rigidity is thus an unstable disequilibrium of the integration of the simple organization of progression and righting resulting from the loss of all those factors that normally modify them. The innate patterns of motor organization that are laid down in the pontine and mesencephalic reticulum are primarily concerned with the regulation of the spinal stretch reflex. This resistance to shock (the 'isolation dystrophy' of spinal segments) reflects a functional independence that probably is derived from their primal position in the whole neural organization. The most simple reactions of progression and righting that rapidly emerged from the rigid state share this autonomy. Such reactions, however, require afferent mechanisms that can discriminate adequacy of stimulus, for which we have given some remarkable examples relating to opening and closing of the hand or foot. Limited lesions of the tectum did not abolish such afferent organization in the two chronic 'decerebrate' monkeys we have described, but it is likely that the afferent mechanism is as

Fig 6 The pretectal lesion in monkey BG 37 is shown in A, and in B the resulting tonic torsion of right limbs and head.
extensive as is the reticular substance. It was apparent that the complex motor automatisms that eventually recovered in the second (cerebellar) animal nevertheless failed to restore the highly integrated individual existing before the cerebellar and tectal lesion. What was missing was evidence of reaction to any total environmental situation, and the normal 'drive' that activates behaviour. The animal was reduced to the status of an automaton. Since cerebellar vermis lesions alone have no such effect our attention was turned to the function of the quadrigeminal plate.

The Mesencephalic Tectum
Stimulation of the tectum opticum leads to a wide variety of movements, including movements of the eyes and of the limbs. Dilation of the pupils, and deviation of the eyes to the opposite side are common effects from stimulation of the superior colliculus, pricking of the ears and vocalization from the inferior pair. In the monkey, Ferrier (1876) first described the wide opening of the eyes with elevation of the eyebrows and turning of the head and eyes away from the side of stimulation that is characteristic of the full effect. This is possibly only a general reaction, and not a definitive mechanism for these movements. Ablation of the corpora quadrigemina has been reported many times since Flourens (1824), who considered total blindness to be the sole result in birds and rabbits. Bechterew (1883) and Münzer & Wiener (1898) and others found that blindness was incomplete. Many of the early experimenters reported forced movements and immobility of the pupils, but these were later thought to be due to damage to neighbouring structures, the posterior longitudinal fasciculus and posterior commissure (Stefani 1881, Sgobbo 1900). Stefani described the disturbance of vision in the pigeon as closely resembling that which follows removal of the cerebral hemispheres. The bird could fly and avoid obstacles, drop down and perch on objects, but would not be able to find corn even when hungry and would not attempt to escape when the observer reached out to pick it up. Sgobbo (1900) destroyed the colliculi in dogs and described a similar amblyopia, present in the opposite visual field from a unilateral lesion. Removal of the inferior colliculus caused some defect in hearing and also some visual impairment. Movements of the eyes and pupillary reactions were unaffected. It was supposed that the absence of this type of visual disturbance in man is due to the increased importance of the geniculocalcarine pathway. In the monkey and in man the colliculus nevertheless receives a sizable complement of fibres from the lateral geniculate body, and these are distinct from those that pass to the pretectal nucleus and posterior commissure, thought to serve the pupillary light reflex (Keller & Stewart 1932, Magoun 1935).

Removal of the superior colliculus in the monkey without damage to the calcarine cortex, radiation or pulvinar is a most difficult procedure. Pasik et al. (1961) reported such removal in four monkeys, and with removal of striate cortex in two others. Optokinetic responses were still present except in one animal lacking striate cortex as well as colliculi. Ocular movements and vestibular nystagmus were unaffected. They found no evidence that the colliculi were critical for any vision remaining after removal of striate cortex. No amblyopia was reported in animals with intact geniculostriate system.

We ourselves have accomplished removal of 75% to 100% of the superior colliculus in five macaques with survivals of 27 to 91 days. The operation was done from behind by gentle displacement of the occipital pole laterally, and introduction of a sucker by direct vision, one side at a time. In two animals there was patchy superficial damage to one occipital lobe on its outer surface, but any degeneration in the lateral geniculate bodies was difficult to find. In another there was no such damage and in two microscopic sections are not yet available, though no gross damage could be seen. The effect of these large lesions of the superior colliculus in the monkey has in our hands been most dramatic. In the days immediately following unilateral removal the animal behaved as if there was a complete hemianopia on the side opposite the lesion. His general behaviour was greatly altered, and he was now mute with totally expressionless facies. All the mimetic responses characteristic of the social habits of monkeys were absent. He showed no fear of the examiner. As some object moved into the visual field on the side of the lesion he showed a violent start and moved away, usually circling round to the side of the lesion. Within three to five days he reacted to the appearance of the examiner in the intact field of vision by retreat to the back of the cage, and by watching intently in the same general direction from which the examiner had come. He seemed to lose the object of his interest quickly, and would go on for some minutes looking expectantly at the place where the stimulus had entered his remaining visual field, sometimes making reaching movements with one or other arm. He had no difficulty in reaching out to a moving object with either hand, and had little difficulty taking hold of it if it was within reach. Nevertheless the eyes did not fix and looked only approximately in the direction of the object. The ear opposite the side of the lesion was no longer pricked to a sudden sound. The pupils were always equal. There was a slight divergent strabismus, but ability to look
up, down, or to either side was not impaired. The optokinetic response was present only when the stripes moved into the visual field from the operated side.

The removal of the remaining superior colliculus (and in one monkey where both sides were removed at one operation) resulted in a profound disturbance of visual and general behaviour (Fig 7). In three animals (BG 25, 33, 36) a moving object larger than 2 cm square could secure the attention of the animal, and he would reach towards the object if it came within 50 cm of him. His reaching was approximately accurate, and was not associated with visual fixation (Fig 7c). In one animal (BG 25) this reaction to moving objects was present in both visual fields from the day after operation and was associated with accurate visual placing in both fields (Fig 7a). After five weeks this animal was able to locate and reach for a still object 2 cm × 3 cm for the first time (Fig 7d). This animal had the least extensive removal of the superior colliculus, sparing its anterior one-quarter on the right side, and rather less on the left (Fig 8). The oral one-third of the posterior colliculus was removed in all animals. In three other animals vision for moving objects returned on one side after periods of one, three and 34 days respectively. This last animal (BG 32) appeared to be completely unreactive to visual stimuli for 34 days, and after the fifth week reacted only to very large moving objects in one visual field.

The last of the five animals (BG 31) remained completely unreactive to visual stimuli (except for

Fig 8 The tectal lesion in BG 25, the animal shown in Fig 7

Fig 9 Monkey BG 31, with no visual reaction for a period of five weeks. The convergent strabismus is shown in A. In B the animal falls from a shelf while feeling his way around a strange cage. In C from above down is shown the absence of reaction to the approach of the observer's hand and the violent flight reaction when he is touched.
Even more extraordinary than the loss of vision following bilateral ablation of the colliculi was the change in general behaviour of these monkeys. Whether some vision for movement and placing remained or not the animals appeared to be totally unaware of events in their environment. They would explore for food when hungry, and showed the usual periods of sleep in a natural posture. The remainder of the time was spent in staring aimlessly into space (Fig 7a). They took no care of their fur or toilet. After an initial start when picked up they would sit on the observer’s arm or nestle in a corner and stare. If stimulated they would run in a straight line until they encountered an obstacle, then would sit still in dazed uncertainty. If suddenly disturbed they showed a pilomotor response but their burst of activity soon evaporated, with relapse into apathy. Only once did one of these animals utter any sound; when he was suddenly grasped by an examiner, after not being handled for a week, he uttered a sharp cry before submitting in silence.

If recovery of an optokinetic reaction occurred on one side, it was associated with circling to that side whenever the animal walked. The circling could be stopped by surrounding the animal with a striped drum rotating in the same direction at a faster rate and could be started by rotation of the drum in the opposite direction. If improvement continued, visual placing appeared several days to two weeks after the return of optokinetic eye and head movement, and later, vision for moving objects. The reaction of the pupil to light was reduced in amplitude in proportion to the loss of visual function, being lost when no visual function returned (BG 31). The lesions then necessarily also damaged the closely related pretectal nucleus. The pupils remained large and equal in all animals. The dorsal grey matter of the aqueduct of Sylvius was removed in three of the five animals, but without damage to the nucleus of the III nerve, or to the ventral part of the central grey, or to the brachium conjunctivum. There was no difference in behaviour in those two where the central grey matter remained intact. The lesion involved the rostral quarter or third of the inferior colliculus in all animals.
**The Pattern-setter of the Nervous System**

It is extraordinary that the removal of a relatively small area of the neoraxis, the tectum of the midbrain, should inactivate the elaborate hemispheric organization for reaction to events in the external world. It is even more remarkable that this should occur in relation to a nucleus without direct cortical representation. The evoked cortical potential is still intact, with the structural apparatus thought to be essential to mammalian vision. The defect is in the reactivity of the organism to the environment, evident in a gross reduction in all types of externally directed behaviour. The tectum appears to be the primary driver of the mesencephalic reticulum of which Starzl et al. (1951) demonstrated the cerebral ‘alerting’ activity. The reaction is clearly allied to the loss of ‘facio-vocal’ activity reported by Kelly et al. (1946) in cats, from peri-aqueductal and tegmental lesions, but our own experiments indicate that behaviour is defective in a more general sense, related to the loss of the perceptual facilitating apparatus of the tectum. Sprague et al. (1961), observing similar mutism and indifference following lateral tegmental lesions in the cat, have attributed these symptoms to sensory deprivation due to damage to the lemniscus. There was no such damage in our animals. To the Sherringtonian physiologist the concept of an ‘alerting’ system without relation to some coherent integrating mechanism has been difficult to comprehend. Our observations on the colliculi indicate that, just as the innate patterns of movement and righting are laid down in the structure of the elementary mesencephalic tegmentum, the comparable templates of the most instinctive inborn patterns for afferent perception are laid down in the tectum.

The lack of reaction of the decerebrate state has always been regarded as a motor phenomenon, as if that explained all its aspects. The problem has long been known to the neurologist in a different form, namely as "akinetic mutism", or "coma vigil". In other circumstances this reaction is associated with dystonia. The peculiarity of collicular lesions is the absence of motor defect except for visual fixation. Such a condition is rare in the clinic, except in relation to diffuse tumours. We therefore present an example, that of a patient whose brain was sent to our laboratory some years ago by Dr James Poppen, who kindly allows me to cite the case:

A 17-year-old schoolgirl sustained a severe head injury as a result of being thrown from a horse. She was found deeply unconscious with left pupil dilated and fixed, right pupil miotic. The lower extremities were rigid in extension, the upper in flexion. A lumbar puncture showed grossly bloody spinal fluid. X-rays of the skull revealed no fracture. The coma continued, with intermittent opisthotonic spasms. A subdural clot was removed from over the left hemisphere. None was found on the right, though the brain appeared edematous. The decorticate posture lessened in severity and became intermittent, with aimless restless movements of the left arm and chewing movements of the jaw in the intervals. Pneumoencephalography showed only a general dilation of the ventricular system. The spasms and involuntary movements gradually lessened in frequency and degree, and had entirely disappeared by the third month after the accident. Throughout her illness the patient showed no expression and stared into space for hours at a time. She showed no evidence of recognition of people or of any event in her surroundings. She died in this state eight months after the injury.

Autopsy disclosed no significant cerebral atrophy or deformity. Small superficial yellow traumatic excavations $3.5 \times 1.5$ cm were found on two temporal gyri on the right side, but were very shallow. Several small yellow or grey lacunar lesions were found in the central white matter of all lobes of the brain, but there was no disintegration of white matter. There was a small lesion in the right habenular and pretectal nucleus, and the left cerebral peduncle was damaged where the tentorial edge had been once impacted against it. The left lateral tegmentum of the midbrain and the superior colliculus, chiefly on the left side, showed severe scarring and loss of substance (Fig 12).

This case demonstrates the importance of the colliculi to perception in the human brain. Though such relatively isolated lesions are rare we would draw attention to the common affection of this region in tentorial herniation, and the probable implication of parts of it in conditions such as peduncular hallucinosis and the more severe manifestations of Wernicke's encephalopathy.
Conclusion

I hope the observations reported here will serve to illuminate the importance of the discovery of decerebrate rigidity. Attention has for too long been focused on the transient rigid component. The total phenomenon illuminates the vital part the mechanism of the mesencephalic and tectal reticulum plays in all cerebral function. This primitive organization of small neurons is evidently the vital facilitator of thalamo-cortical function. Just as cortical activity is dependent on thalamic integrity, so both also require the colliculi. Some surgeons have long been impressed by the importance of the peri-aqueductal grey matter to the general manifestations of consciousness (Bailey & Davis 1942). Skultety et al. (1954) showed that lesions of the peri-aqueductal grey matter alone in cats did not disturb reactivity. The physiological evidence has been difficult to establish, and our own observations show no direct relationship to mechanisms for sleep. Consciousness is a term that implies a subjective element which the physiologist tries to avoid.

The mesencephalic tectum is, however, essential for the reactions we call general awareness, for which it has an initiator function, just as its ventral component, the mesencephalic reticular substance, is vital to organization of movement. Further, though there is reason to believe that the reactions concerned are at the primitive instinctive level, our experiments indicate that they are the essential substrate for all the more highly developed behavioural reactions.

We hesitate to use the word ‘primitive’, but perhaps I may quote from C J Herrick (1921) regarding the comparable region of the truly primitive tubular nervous system of cyclostomes. The grey matter in these animals borders the central canal and the processes of the cells radiate outwards. He says: ‘The nervous organization is such as to make possible a relatively small number of reactions for all sorts of sensory stimulations, and these reactions are for the most part simple total movements of the whole body ... rather than complex adjustments involving precise co-ordination of many separate organs.’

The pericanicular grey matter of the mid-brain has long been regarded as the essential area for brain function in fishes but its role had been thought to have been transferred to the hemispheres in all higher vertebrates (Monakow 1895). In the primate nervous system this is still the vital centre of the brain. Its more differentiated peripheral layers, the reticulum and tectum, are more essential than the immediately peri-aqueductal core. Though physiologists have resisted Henri Bergson’s notion of an élán vital as being too imprecise for scientific proof, this small area deserves consideration as the most vital for unitary function of the organism. It is the physiological ‘ego’, the mainspring of la vie en relation.

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