Electrophysiological study of the peripheral nervous system in children

Changes in proximal and distal conduction velocities from birth to age 5 years

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SUMMARY Hoffman's reflex was evoked in the soleus muscle of 105 normal children from birth to age 5 years. This technique made it possible to determine conduction time and to estimate conduction velocity over the reflex arc. For 59 children, proprioceptive and motor distal nerve conduction velocities were calculated for the tibial nerve trunk. These measurements enabled the common changes for these three velocities to be described in terms of an exponential curve. Proximal conduction velocity has similar values to those of proprioceptive distal nerve fibres: it is always higher than motor nerve conduction velocity, but the difference gradually diminishes, remaining constant after the eighteenth month. Conduction time diminishes between birth and one year of age, whereas height increases. Then conduction time increases slowly, reaching at about age 5 years, when average height is 1050 mm, the value it had just after birth. For the child born at term, maturation of the nervous system is thus especially rapid during the first year of life.

Nerve conduction velocities were first studied in the newborn and young children by Thomas and Lambert (1960). Subsequent studies concerning children (Gamstorp, 1963; Raimbault and Laget, 1963; Schulte *et al.*, 1968; Duron *et al.*, 1977) related to the measurement of conduction velocities over the distal nerve trunks of the upper and lower extremities. Mayer and Mosser (1969, 1973) applied the technique of Hoffman's (H) reflex to the lower extremity, principally to study the excitability of motoneurons.

It seemed advisable to us to carry out a study concerning the longest nerves in the body, those often first affected by peripheral neuropathy. We evoked the H monosynaptic reflex in the soleus muscle of 105 children. This technique allowed us to determine the conduction velocity over the reflex arc by means of a simple and easily applied formula. We complemented this measurement with a calculation of the motor and proprioceptive conduction velocities of the tibial nerve trunk in 59

children. We were thus able to compare the respective changes in velocity, according to age, for the proximal and distal segments of the same nerve pathway as well as the motor and proprioceptive velocities in the same nerve trunk. It was also possible to specify changes in conduction time according to the height and age of the children.

Subjects and methods

One hundred and five normal children were divided into seven groups according to age: 1 to 30 days (14), 1 to 6 months (13), 6 to 12 months (16), 12 to 18 months (13), 18 months to 2 years (17), 2 to 3 years (18), 3 to 5 years (14). The infants were all born at term and were neurologically normal. The other children, hospitalised for minor ailments, were used for the study when they were afebrile and considered cured.

The children were placed in a room maintained between 23° and 25°C. They were either in a reclining position, with the lower limb supported by a restraining table made in the laboratory, or in a prone position, with the foot resting on a

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fixed bar. In both cases, the limb position was 120° flexion of the knee joint and 90° flexion of the ankle (Hugon, 1973).

The H reflex was evoked in the soleus muscle by cathodic monopolar stimulation of the sciatic nerve in the popliteal fossa. The stimulating electrode was mounted on a Simon's stirrup reduced in scale by one half. An anode was placed on the lateral surface of the thigh. The potential evoked in the soleus muscle was recorded by two surface electrodes, the proximal placed on the muscle belly, the reference, at 30 mm distally, on the achilles tendon.

Tibial nerve conduction velocity was obtained for 59 children by stimulating the nerve electrically in the popliteal fossa and in the retromalleolar groove. Muscle response was recorded by two surface electrodes on the abductor hallucis muscle.

Stimulation at each point of the nerve pathway first evoked an H monosynaptic response and then an M motor response.

MEASUREMENTS

Estimated proximal conduction velocity

The technique of recording the soleus H reflex allows measurement of the conduction time over the reflex circuit: popliteal fossa—spinal cord—central synapse—popliteal fossa. It corresponds to the difference in latencies of the two maximal H and M responses, with the point of sign reversal between two identical waves of the maximal responses taken as reference point (Paillard, 1955).

The length of the reflex circuit corresponding to this conduction time is equal to twice the distance separating the stimulation point from the spinal cord. This length is equal to 80% of height (see Discussion).

The estimated conduction velocity over the H reflex circuit evoked in the soleus, or the estimated proximal velocity, may be formulated as follows:

$$V = \frac{80\% \text{ Height}}{(\text{lat H} - \text{lat M}) - 1} \quad \begin{array}{l} \text{V in m/s} \\ \text{Height in mm} \\ \text{Latency in ms} \end{array}$$

Distal conduction velocities

Distal conduction velocities over the tibial nerve trunk are calculated according to the customary formula: $V_{m/s} = (d \text{ mm} / t \text{ ms})$ where d represents the distance between two points of stimulation, t the time taken to cover that distance: either, for proprioceptive nerve conduction velocities, the difference between the latencies of the two H responses obtained from the abductor hallucis

muscle, according to the technique of Liberson (1963); or, for motor nerve conduction velocities, the difference between the latencies of the two M responses obtained from the same muscle.

Statistical calculations

For each group of subjects, statistical data were determined according to Student's t test, and the mean and the standard deviation were calculated for each series of results. Divergences among the groups were interpreted by calculating the distribution of the differences among the means of each group.

Studies of linear correlation were made according to the customary methods of regression by the least squares.

To determine nonlinear relationships, the dispersion of points on the graph was divided up, according to the axis of the abscissas, into zones containing the same number of points. The mean was calculated according to X and Y values for the points contained in each zone. The increment between two zones was defined to make a satisfactorily smooth plotting of the curves possible.

Results (Table)

CONDUCTION TIME FOR THE REFLEX CIRCUIT

Conduction time over the reflex circuit changes little during the first five years of human existence (Fig. 1). However, during the first 12 months, the conduction time diminishes slightly but significantly, from 15 ms during the first days of life to 12 ms at about a year of age. At the same time the length of the reflex circuit increases markedly, as may be judged by the growth in height of the children in our population from 500 to 680 mm. From the age of one year on, conduction time increases very gradually, reaching once again, at age five years, the value it had at birth, whereas height increases to 1050 mm. Once this height is reached, conduction time progresses linearly with height (Fig. 1); the correlation coefficient is 0.96.

ESTIMATED CONDUCTION VELOCITY IN THE H REFLEX CIRCUIT WITH RESPECT TO AGE

The conduction velocity changes according to an exponential curve (Fig. 2a). The increase in velocity is rapid at first, during the first 12 months of existence. From 31 ± 3 m/s during the first month of life, the velocity value goes to 39 ± 3 m/s during the next five months, then to 47.5 ± 5 between six months and one year of age. After this rapid rise, the curve levels off although it continues to rise slightly. The mean conduction

Table Mean values and standard deviations for conduction time and proximal and distal nerve conduction velocity (both proprioceptive and motor) in children from birth to age 5 years

Age (yr)	Height (mm)	Number of children	Conduction time over the reflex arc (m/s)	Mean estimated conduction velocity over the reflex arc (m/s)	Number of children	Proprioceptive NCV over the tibial nerve trunk (m/s)	Motor NCV over the tibial nerve trunk (m/s)
0-30 days	505 (450-555)	14	14.0 ± 1.0	31.0 ± 3.0	8	29.0 ± 4.0	20.5 ± 3.5
1- 6 months	570 (490-660)	13	12.8 ± 1.5	39.0 ± 3.0	7	39.5 ± 6.0	26.5 ± 4.0
6-12 months	685 (570-765)	16	12.5 ± 1.0	47.4 ± 5.0	13	46.0 ± 5.0	35.25 ± 4.0
12-18 months	757 (680-830)	13	12.8 ± 0.75	51.5 ± 3.0	8	50.5 ± 4.0	41.5 ± 4.0
18-24 months	816 (710-890)	17	13.0 ± 0.6	55.0 ± 3.0	8	55.0 ± 4.0	45.0 ± 5.0
2- 3 years	893 (840-990)	18	13.5 ± 0.6	58.0 ± 2.5	7	59.0 ± 4.0	46.2 ± 1.5
3- 5 years	980 (895-1150)	14	14.0 ± 0.9	60.6 ± 3.0	8	60.0 ± 5.0	48.4 ± 3.5

NCV = nerve conduction velocity.

Fig. 1 Changes in conduction time for the monosynaptic reflex circuit of the soleus muscle from birth to age 30 years, plotted according to height. ● = values for children to age 5 years, ○ = values for subjects ages 7 to 30 years.

velocity is 51.5 ± 3 m/s between 12 and 18 months, 55 ± 3 m/s between 18 months and 2 years, 58 ± 2.5 m/s between 2 and 3 years, and 60.5 ± 3 m/s between 3 and 5 years. The conduction velocity value of an adult is reached between 3 and 5 years (Fig. 2a).

We looked for a mathematical law to account for the changes in proximal conduction velocity during the first five years of life. In that the curve is exponential, we determined, after a succession of approximations (evening off, testing mathematical equations), that the following mathematical formula is best suited to its form:

$$y = \frac{66x + 7500}{x + 160} \quad \begin{matrix} y \text{ in m/s} \\ x \text{ in days} \end{matrix}$$

The first derivative of this curve is thus

$$y' = \frac{9660}{(x + 160)^2} \quad \begin{matrix} y' \text{ in m.s}^{-1} \text{ d}^{-1} \end{matrix}$$

Fig. 2 (a) Changes in estimated nerve conduction velocity over the reflex arc for 105 children from birth to age 5 years and for 31 subjects aged 10 to 40 years. (b) Curve of changes in proximal nerve conduction velocity and its first derivative, maturation velocity, plotted according to age.

The derivation thus obtained (Fig. 2b) corresponds to the changes in maturation velocity, which decreases very rapidly during the first year, then slowly, before becoming nil at about age 3 years.

CONDUCTION VELOCITIES FOR THE TIBIAL NERVE TRUNK
Conduction velocity for the motor fibres of the

tibial nerve changes, according to age, in terms of an exponential curve (Fig. 3). The progression in motor conduction velocity is rapid at first, going from 20.5 ± 3.5 m/s during the first month of life to 26.5 ± 4 m/s between the first and sixth months, to 35 ± 4 m/s between 6 and 12 months, to 41.5 ± 4 m/s between 12 and 18 months, and, finally, to 46 ± 1.5 m/s between 18 months and 2 years. Beyond age 2 years, conduction velocity increases only slowly, reaching 48.5 ± 3.5 m/s between 3 and 5 years of age. The curve tends to become asymptotic. It is from the age of 2 years on that the conduction velocity value of an adult is reached. Maturation velocity decreases very rapidly, then slowly, before becoming nil at about age 3 years.

Conduction velocity for the proprioceptive fibres of the tibial nerve also changes in terms of an exponential curve (Fig. 3). The rise is rapid during the first 18 months of existence, going from an average of 29 ± 4 m/s during the first month to 39 ± 6 m/s during the next five months, then to 46 ± 5 m/s between 6 and 12 months, and finally to 59.5 ± 4 m/s between 12 and 18 months. Afterwards, the increase is slower: the velocity reaches 60 ± 5 m/s between 3 and 5 years of age.

Thus, proprioceptive nerve fibres conduct the nerve impulse more rapidly than do motor nerve fibres. Depending on age, proprioceptive nerve conduction velocity is 8–13 m/s faster than motor nerve conduction velocity.

CORRELATION BETWEEN PROXIMAL AND DISTAL NERVE CONDUCTION VELOCITY FOR THE TIBIAL NERVE TRUNK

During the first five years of life, the conduction velocities measured change in the same way, in

Fig. 3 Changes in the means of distal proprioceptive (above) and motor (below) nerve conduction velocities over the tibial nerve trunk in children. Δ mean value, I standard deviation.

terms of an exponential curve. This is true at the level of the proximal and distal segments of the nerve pathway as well as at the level of the motor and proprioceptive fibres of the same nerve trunk. The proximal and proprioceptive distal velocities have superimposable values, and the differences between them are not statistically significant. The curves for changes in proximal and motor distal velocities are identical in contour. Moreover, the relationship linking the values of these two velocities is linear (Fig. 4a): the straight line corresponds to the equation, $y = 0.997x - 11.1$; the correlation coefficient is equal to 0.989.

Comparison of these two velocities shows that conduction, during the whole growth period, is more rapid for the H reflex circuit (Fig. 4b). In terms of absolute value, the difference between the proximal and motor distal velocities remains nearly stable, varying from 9.5 to 12.5 m/s. In

Fig. 4 (a) Relation between motor nerve conduction velocity over the tibial nerve and estimated proximal nerve conduction velocity in children from birth to age 5 years. (b) Changes in the means of proximal (above) and motor distal (below) nerve conduction velocity in children. + = points obtained by calculating successive means (means of 20 units per zone, with a step of 1 unit), . . . = standard deviation.

terms of relative value, this difference changes with age. After being 51% higher than motor distal velocity in the first months of life, proximal velocity is only 24% higher at about 18 months. Thereafter, the difference remains constant.

Discussion

Changes in conduction time during maturation may be explained by the respective modifications in the length of the reflex arc and in conduction velocity. During the first year of life, the nerve fibres develop much more in thickness than in length, so that conduction velocity has its period of most rapid increase, more than compensating for the lengthening of the nerve circuit, and conduction time diminishes. Then the increase in conduction velocity becomes slighter, while the length of the nerve circuit continues to grow. In these circumstances, conduction time at first remains stable, then increases very gradually. From the moment when conduction velocity has reached its maximal value, nerve conduction time becomes proportional to body height. These changes in conduction time are peculiar to man and differ from those described for animals. Some authors (Verley, 1976) have emphasised the functional implications of such changes.

The formula proposed for calculating the conduction velocity of the soleus reflex arc uses as conduction time the difference in the latencies of the maximal H and M responses. This choice of conduction time has at least two advantages—it represents the time taken for a circuit over afferent and efferent pathways of equal length, and it allows elimination of the time for neuromuscular synaptic transmission. One millisecond has been deducted in the formula to allow for crossing the synapse in the spinal cord, a time estimated from studies in animals (Skoglund, 1960) and in man (Magladery *et al.*, 1951).

The length of the corresponding reflex arc cannot be determined directly. We estimate it as 80% of body height, an estimate based on studies of adult cadavers (Guiheneuc, 1971) and on knowledge of the respective development of the femur and of the trunk (Maresh, 1955, 1959) during the first year of life. Thus it seemed possible to us to estimate proximal nerve conduction velocity during the growth period by means of a simple formula.

Knowing the nerve conduction velocity for the tibial nerve trunk enabled us to correlate the velocities for the proximal and distal segments of the same nerve pathway. The results are more

uniform than those for other nerves such as the peroneal nerve (probably because of its anatomical course), as Raimbault and Laget (1963) noted, and as we have confirmed.

The changes in these conduction velocities during the first years of life take the form of an exponential curve. Equal to half the adult values at birth, these velocities reach their maximal values between ages 3 and 5 years. Moreover, this mode of progression has been noted for other nerve trunks, whether for motor nerve conduction velocities (Wagmann and Lesse, 1952; Thomas and Lambert, 1960; Gamstorp, 1963) or for sensory nerve conduction velocities (Raimbault and Laget, 1963; Gamstorp and Shelburne, 1965; Duron *et al.*, 1977).

These electrophysiological results conform to histological data. At birth, the sciatic trunk has half its diameter at maturity. The diameter of the large myelinated nerve fibres reaches its adult size at about 5 years (Rexed, 1944; Gutrecht and Dyck, 1970). After birth, the number of myelinated fibres increases very markedly. Myelination progresses according to an exponential law (Skoglund and Romero, 1965; Friede and Samorajski, 1968; Gutrecht and Dyck, 1970; Webster, 1975), and axonal diameter and thickness of the myelin sheath remain proportional during their development (Friede, 1972). In addition, the nodes of Ranvier are remodelled, and the metabolic exchanges between the paranodal Schwann cell and the axon intensify (Berthold and Skoglund, 1967). All these factors facilitate nerve conduction velocity and explain the rapid increase in velocities during the first 18 months of life.

The similar changes in conduction velocity over the proximal and distal segments of the nerve pathway tend to demonstrate that maturation is parallel for the two segments. However, the greater rapidity of conduction velocities over the proximal segment may be explained by three factors. First, myelination progresses ordinarily from the roots towards the periphery (Skoglund, 1960; Fraher, 1976). Secondly, proximal conduction velocity is the average speed of the afferent and efferent velocities. The conduction velocity of the H reflex over the afferent fibres is higher than over the motor fibres (Magladery and McDougal, 1950; Thomas and Lambert, 1960), just as the velocity over the proprioceptive fibres of a nerve trunk is greater than that over the motor fibres, as Raimbault and Laget (1963) and we ourselves have reported for the tibial nerve, as Dawson (1956) has shown for the median nerve in adults, and Willer (1975) for the peroneal nerve. Thirdly,

Skoglund and Romero (1965) found that in kittens the largest nerve fibres branch out from the nerve trunk along with the fibres to the proximal muscles. However, such an anatomical arrangement does not seem to be as definite in the newborn child (Nyström and Skoglund, 1966).

The difference between proximal and motor distal conduction velocities diminishes with age, according to a more rapid progression in conduction velocities over the tibial nerve trunk in comparison with the velocity for the proximal segment of the nerve trunk.

It is thus during the first year of life that the main processes responsible for the maturation of the nervous system develop. During this period, nerve conduction velocities increase most rapidly, and conduction time diminishes. These processes of maturation precede those of skeletal growth.

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