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Callosal and corticospinal tract function in patients with hydrocephalus: a morphometric and transcranial magnetic stimulation study

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Abstract In 15 patients with symptomatic hydrocephalus, pressure-induced morphological changes of the brain and the function of callosal and corticospinal fibres were studied. Morphometry of the corpus callosum (CC) was performed on midsagittal MR images. Focal transcranial magnetic stimulation of the motor cortex was used to assess simultaneously excitatory motor responses in contralateral hand muscle (corticospinally mediated effect) and inhibition of tonic EMG activity in ipsilateral hand muscles (transcallosal inhibition (TI) of the contralateral motor cortex). Before a shunt operation, the midsagittal area of the CC was reduced by 34% on average. The height and, to a lesser degree the length, of the CC were increased before the shunt operation. Thresholds and central motor latencies of corticospinally mediated responses were normal, response amplitudes were smaller than in normal subjects. Motor thresholds increased from 38, SD 5 to 52, SD 8% (P<0.01) within 7 days after ventricular drainage, reflecting the increase in the distance between stimulation coil and brain. The threshold increase paralleled a restoration of normal anatomical conditions within 7 days after shunt operation and the improvement of motor symptoms and might be a predictor of successful decompression. Transcallosal inhibition could be elicited in all patients. The measurements of TI lay within the normal range except the duration, which was prolonged in 73% of 15 patients before shunt operation as a probable indicator of an increased dispersion of callosal conduction. The normalization of the area and shape of the CC after shunt operation and the normal corticospinal and callosal conduction times exclude degeneration, demyelination or functional block of a large proportion of callosal or corticospinal tract fibres or a substantial loss of nerve cells in motor cortex.

Key words Corpus callosum · Corticospinal tract · Hydrocephalus · Brain morphometry · Transcranial magnetic brain stimulation

Introduction

In hydrocephalus, gross pressure-induced morphological changes of the brain may occur such as dilatation of the ventricles, thinning and upward bowing of the corpus callosum (CC), diminution of high-convexity sulci and of cisterns and an interstitial oedema due to transependymal migration of cerebrospinal fluid [10–12, 29]. Motor symptoms and clinical signs such as parkinsonian or ataxic gait, impaired complex movements such as handwriting, tremor, increased muscle tone and brisk reflexes, and sometimes extensor plantar responses [7, 10, 21, 30], have been related to the increased intracranial pressure, with presumed secondary stretching and compression of long tracts in the cerebral white matter of the frontal lobe, the corona radiata and the corpus callosum. [1, 7, 10].

Since the functional relevance of morphological changes in hydrocephalus in relation to motor function and their reversible or irreversible nature are still unclear [33], we tried to approach this problem by the use of transcranial magnetic stimulation (TMS) of the cortex as a tool to investigate corticospinal [25] and callosal tract function [6, 18] and by correlating the findings with the morphological changes of the corpus callosum on magnetic resonance (MR) images. The questions of the reversibility of morphological and functional changes and of whether the known thinning of the CC in hydrocephalus [3, 11, 26] reflects an irreversible fibre degeneration or simply a potentially reversible stretching of callosal fibres were addressed by serial MR imaging and neurophysiological investigations before and after ventricular shunting in a subgroup of the investigated patients.

TMS is now well established as a diagnostic instrument with which to assess the excitability (response threshold and amplitude) and conductivity (central motor latencies) of fast monosynaptic corticospinal connections [25]. Furthermore TMS can be used to investigate the function of callosal fibres that pass through the trunk of the CC and connect the primary motor cortices of both hemispheres [18–20]. This approach is based on the observation that focal magnetic stimulation over the motor cortex of one hemisphere suppresses ongoing voluntary electromyographic (EMG) activity originating from the contralateral motor cortex [6].

The effects of TMS on the motor cortex were investigated in hand muscles, since only the distance between the hand motor representations of both hemispheres is long enough to guarantee hemisphere-selective motor cortex activation, which is a crucial prerequisite of assessing callosally mediated effects.

Methods

Patients

With ethical committee approval, fifteen patients with chronic hydrocephalus (mean age 57 years, range 20–85; 12 men, 3 woman) were investigated before, and five of them also after, shunt insertion (Table 1). Following the classification of Prokop [23], five patients had obstructive (Table 1, patients 1–5), five communicating (patients 6–10), and five normal pressure hydrocephalus (patients 11–15). The diagnoses were made on clinical grounds, on the basis of radiographical assessment of cerebrospinal fluid dynamics, and on MR imaging (MRI).

All investigated patients had been symptomatic for more than 2 months (Table 1) and were still able to walk (in two patients with aid) at the time of the investigation. Clinical symptoms of the patients are summarized in Table 1. In nine patients the arm and, more markedly, the leg tendon reflexes were increased; in patient 10 the plantar responses was unilaterally extensor. All patients in whom ventricular shunting was performed improved in regard to movement velocity and postural stability of gait. Furthermore the reflex level diminished after shunting. None of the patients were receiving medication that had any influence on central nervous system excitability. All investigated persons gave their informed consent prior to their inclusion in the study.

Magnetic stimulation and recording

General procedure: Focal TMS of the motor cortex of each hemisphere was performed consecutively with an eight-shaped coil (o.d. of half-coil, 8.5 cm) of the Magstim 200 stimulator (2-T version; Magstim Company, Dyfed, UK) with the coil centre placed over the hand representation area. For each subject, the stimulation point for eliciting maximal hand motor responses was determined individually and lay, on average, 6 cm lateral to the vertex and 1 cm anterior to the interaural line. The coil currents were directed anteroposteriorly (with the handle of the coil pointing backwards) and the induced currents posteroanteriorly (Fig. 1). The elicited surface compound EMG responses (electrode area 70 mm^2) were recorded bilaterally from the first dorsal interosseous muscle. Data were collected using a CED 1401 interface and a data collection program (SIGAVG, sampling frequency of 5000/s per channel).

Thresholds of corticospinally mediated contralateral EMG responses were determined in relaxed muscles. Cortex stimulation was performed with maximally tonically contracted muscles and 80% of the maximum stimulator output, since for such intensities stimulation effects had previously been found to lie in a range of amplitude saturation [18]. After stimulation, 20 consecutive EMG signals elicited by stimulation over each hemisphere were averaged (peak-to-peak amplitudes, onset latency) or rectified and then averaged (other parameters; Fig. 1). To avoid central or peripheral fatigue during maximal tonic muscle contraction, the subjects paused for 3 min after blocks of 10 stimuli. The stimuli were applied over the cortex with a frequency of 0.2 Hz.

To determine peripheral conduction times, magnetic stimulation was performed over the cervical nerve roots with a standard round coil (o.d. 11.6 cm).

Twelve healthy volunteers (aged 24–34 years, mean 28.4) served as a reference.

Response parameters

In muscles contralateral to the side stimulated, the thresholds, amplitudes, and central motor latencies of corticospinally mediated responses were measured. In muscles ipsilateral to stimulation, we determined the onset latency, duration, and the transcallosal latency (TCL) of transcallosal inhibition to investigate the function of callosal fibres. The procedure of measuring the different response parameters is illustrated in Fig. 1.

The *response threshold* (% of maximum stimulator output) of corticospinally mediated responses was determined for the relaxed contralateral hand and defined as the stimulus intensity at which small responses of 0.2 mV occurred in about half of the trials.

The *amplitude* of the contralateral EMG response was determined peak-to-peak for 20 averaged consecutive responses.

Central motor latency times were calculated by subtracting the longest peripheral conduction time following magnetic root stimulation from the onset latency of the fastest cortically elicited contralateral EMG response.

The *onset-latency* of TI was measured from the stimulation artefact to a point where the signal of the averaged tonic EMG activity in the hand ipsilateral to stimulation clearly fell under the mean amplitude of the EMG activity before the stimulus.

The *duration of TI* was measured from the onset of the suppression of EMG activity to a point were the EMG activity again reached the baseline EMG activity before the stimulus.

The *TCL* was calculated by subtracting the onset latency of the contralateral excitatory responses in a given muscle from the onset latency of ipsilateral TI (Fig. 1).

In general, low thresholds, short central motor latencies and large response amplitudes of contralateral excitatory responses indicate a high excitability of the corticospinal system. Short TCLs and long durations of TI of EMG activity in muscles ipsilateral to stimulation indicate a strong activation of the callosal connections.

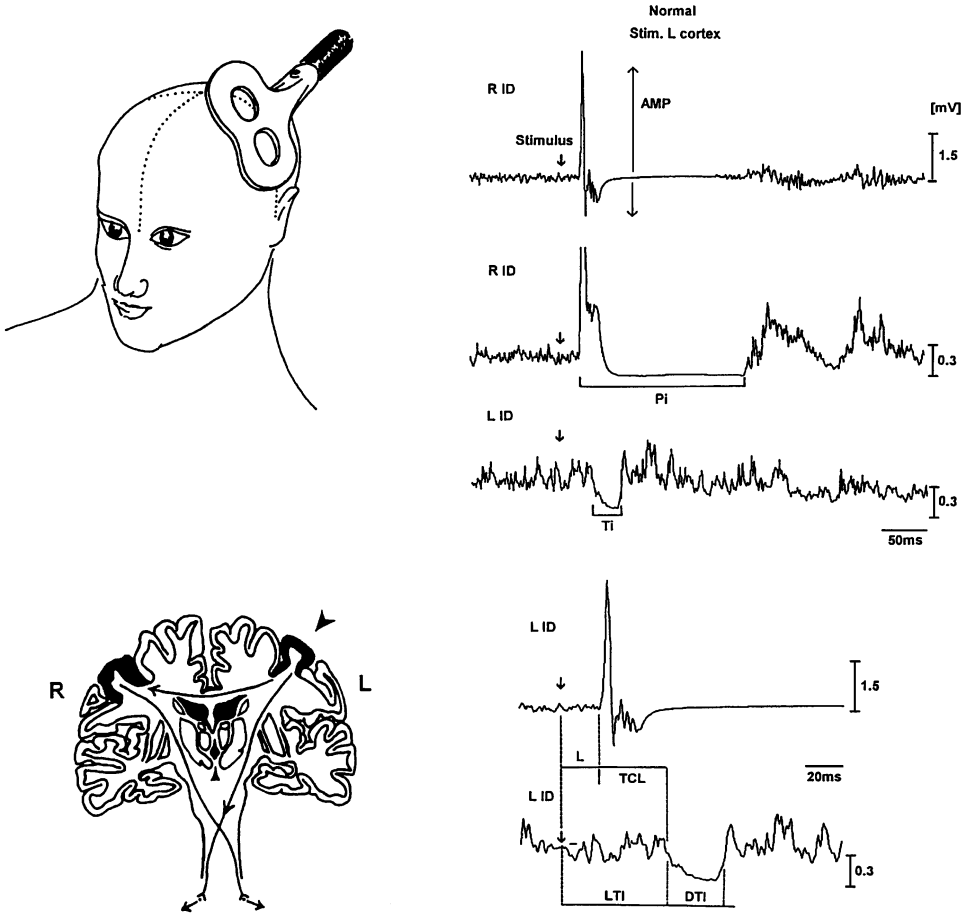

Fig. 1 Principle of transcranial magnetic motor cortex stimulation and mode of determination of different response parameters: Stimulation is performed with anteroposterior coil currents and 80% of the maximum stimulator output and with a focal coil centred over the hand-associated motor cortex (upper left). Stimulation of the motor cortex of one hemisphere activates the corticospinal tract resulting in contralateral hand motor responses (*1st, 2nd and 4th EMG trace on the right*) and callosal fibres which leads to a suppression of tonic EMG activity in maximally contracted ipsilateral hand muscles (*3rd and 5th EMG trace*). To determine transcallosal conduction latency (*TCL*) the onset latency of the corticospinally mediated excitatory motor response (*L*) in a given muscle is subtracted from the onset latency of transcallosal inhibition (*LTI*) in the same muscle (lower right). Averages of 20 rectified (*2nd, 3rd and 5th EMG trace*) and non-rectified surface compound EMG recordings (*1st and 4th trace*) are shown. For further explanations see text. (*R ID, L ID* right and left first dorsal interosseous muscle, *AMP* amplitude, *Ti* transcallosal inhibition, *DTI* duration of TI). Note the different amplifications and time bases of the recordings

The Mann-Whitney rank sum test and the Wilcoxon signed-rank test were used for statistical analysis of the neurophysiological data comparing the patient and the normal subject group and the patients before and after shunt operation.

Imaging and morphometry

For MRI, axial, sagittal and coronal spin-echo T1-weighted, axial spin-echo T2-weighted and axial proton density-weighted sequences in a 1.5-T imager were performed. The height of the CC above a defined baseline, its length as distance between genu and splenium, and its midsagittal area (Table 1) were measured by using Kontron-Videoplan software in all patients except patient 9, who refused MRI owing to claustrophobia. All values in Table 1 represent means of three consecutive measurements on the same slice by the same operator. In five patients, changes of the form and cross-sectional area of the CC due to ventricular shunting were measured on the 7th day after the operation. The morphometrical data were compared with normative data, obtained from 22 healthy subjects (22–92 years, mean age 45 years; 8 men, 14 woman) published by Hofmann and collaborators [11].

Results

Corticospinally mediated contralateral excitatory responses

Before shunt operation, patients had normal central motor latencies (6.7, SD 1.0 ms) (Table 2). In contrast, the responses amplitudes were significantly smaller in the patients than in normal subjects (5.4, SD 1.7 mV in patients compared with 7.5, SD 1.9 mV in normal subjects; P=0.001, Table 2), while the response thresholds lay with-

Table 1 Preoperative symptoms and morphometric data of the corpus callosum obtained by measurements on sagittal MR slices in patients with different types of hydrocephalus. See text and Fig. 4 for definitions of height, length and area of the corpus callosum. All values are means of three consecutive measurements. (*F* female, *M* male, *HO* obstructive, *HC* communicating, *NPH* normal-pressure hydrocephalus, *DOG* disturbance of gait)

Pat.	Sex	Age (years)	Type of hydrocephalus	Preoperative symptoms	Duration of symptoms (months)	Preoperative morphometry of corpus callosum		
						Height (cm)	Length (cm)	Area (cm^2)
1[a]	F	73	HO	DOG	12	3.1	7.6	4.5
2[a]	F	60	HO	Vertigo	3	3.2	7.6	4.5
3	M	58	HO	Lack of concentration, double vision	3	2.9	6.9	5.2
4[a]	M	20	HO	Heachache	3	4.0	8.2	6.1
5[a]	M	58	HO	Heachache	6	2.9	6.9	5.2
6	M	32	HC	DOG double vision	3	5.2	10.1	4.6
7	M	22	HC	DOG, mental retardation	Since birth	3.9	8.0	4.7
8	M	37	HC	Heachache	2	4.3	9.7	2.7
9	M	59	HC	Lack of concentration	3	–	–	–
10	M	68	HC	DOG, lack of concentration	180	4.2	8.0	5.2
11	M	85	NPH	DOG, urinary incontinence	36	3.9	7.2	4.6
12	M	79	NPH	DOG, dementia, urinary incontinence	25	3.2	7.1	4.2
13	F	79	NPH	DOG, dementia	86	3.0	6.8	4.3
14	M	73	NPH	DOG, dementia	13	3.3	7.2	4.0
15[a]	M	52	NPH	DOG, dementia, urinary incontinence	4	3.5	8.0	4.2

[a] MRI morphometry was also investigated 7 days after ventricular drainage

in normal range (36, SD 7% in patients compared with 40, SD 7% in normals; P=0.1, Table 2).

Measurements made seven days after ventricular drainage showed a remarkable increase in the response thresholds when compared with the pre-operative values (52, SD 8 post-operative compared with 38, SD 5 pre-operative; figures reflect % of maximum stimulator output n=10 hands, P<0.003, Table 2), while the central motor latencies and response amplitudes remained unchanged. Examples of original recordings of one patient (patient 4) before and after shunt insertion are shown in Fig. 2. The individual changes of cortical response thresholds after ventricular shunting and the corresponding changes of the area of the CC are illustrated in Fig. 3.

Callosally mediated ipsilateral inhibition of EMG activity

In all patients, transcallosal inhibition of tonic EMG activity could be elicited. The mean onset latency of TI lay within the normal range (37.0, SD 4.1 ms in patients compared with 35.8, SD 3.6 ms in normals; P=0.8; Table 2), but the duration of TI was prolonged in 11 of 15 patients (13 of 30 hands) before (means, 30.3, SD 8.7 ms in patients compared with 24.8, SD 2.7 ms in normals; P <

Table 2 EMG effects of transcranial magnetic cortex stimulation in hand muscles: Different parameters of corticospinally mediated contralateral excitatory effects and transcallosal inhibition of tonic voluntary ipsilateral EMG activity. Data for all investigated patients and a subgroup of patients investigated before and after shunt operation. For comparison, our own normative data are given (mean values (SD), ranges in parentheses). *Δ R/L* right-left difference, *CML* central motor latency, *TI* transcallosal inhibition. Statistical analysis was performed with the Mann-Whitney rank sum test (* normal compared with patients) and the Wilcoxon signed-rank test ($^{\#, \#\#}$ pre-compared with post-shunt operation)

	Normal subjects (12 subjects/24 hands)		All patients (pre-shunt) (15/30)		Patients pre-shunt (5/10)		Patients post-shunt (5/10)	
Corticospinally mediated contralateral excitation								
Response threshold (%Max.)	40 (7)	(33–55)	36 (7)	(21–45)	38 (5)	(28–45)	52 (8)	(43–64)$^{\#}$
Δ R/L	3 (4)	(0–11)	4 (4)	(0–13)				
CML (ms)	6.7 (1.0)	(4.6–8.8)	6.6 (0.8)	(5.2–8.8)	6.7 (0.3)	(5.6–8.6)	6.7 (1.0)	(5.2–8.0)
Δ R/L	0.6 (0.4)	(0–1.2)	0.8 (0.7)	(0–2.2)				
Amplitude (mV)	7.5 (1.9)	(3.1–10.6)	5.4 (1.7)	(2.3–8.6)*	4.7 (1.8)	(2.3–7.4)	4.9 (0.8)	(3.7–5.9)
Δ R/L	1.7 (1.2)	(0.1–4.0)	1.7 (1.8)	(0.3–6.3)				
Transcallosal ipsilateral inhibition								
Latency of TI (ms)	35.8 (3.6)	(25.2–40.4)	37.0 (4.1)	(32.2–51.6)	34.9 (1.9)	(33.2–39.2)	37.4 (2.6)	(34.4–40.8)$^{\#\#}$
Δ R/L	2.6 (2.0)	(0.2–7.0)	3.5 (4.2)	(0.6–16.2)				
Duration of TI (ms)	24.8 (2.7)	(19.2–30.1)	30.3 (8.7)	(17.8–51.2)*	29.5 (6.6)	(21.0–41.4)	32.3 (7.4)	(24.0–44.2)
Δ R/L	3.3 (2.2)	(0.4–7.6)	7.5 (5.3)	(1.6–20.8)				
Transcallosal latency (ms)	15.5 (2.5)	(10.2–20.0)	16.0 (4.3)	(10.0–31.0)	13.8 (2.8)	(10.0–19.2)	15.7 (2.5)	(12.8–20.8)
Δ R/L	2.1 (2.1)	(0.2–7.6)	3.6 (4.5)	(0.4–17.2)				

*P<0.001, $^{\#}P$<0.01, $^{\#\#}P$<0.05

0.01) and in four of five patients (five of ten hands, mean 32.3, SD 7.4 ms) after shunt operation. The side difference of the duration of the TI tended to be higher than in normals (7.5, SD 5.3 ms in patients compared with 3.3, SD 2.2 ms in normals; P<0.1; Table 2). In the patients, the TCL lay within the normal range (16.0, SD 4.3 ms in patients compared with 15.5, SD 2.5 ms in normals; P=0.9; Table 2). Shunt operation led to a significant increase in the onset latency of TI which even then lay within the normal range. Other parameters of TI did not change significantly in relation to shunt operation.

Morphometry of the corpus callosum

Figure 4 illustrates the morphological alteration of the brain through increased intraventricular pressure in patient 4. The compression of the gyri against the skull and the thinning of the CC regressed within 7 days after shunt implantation. After shunt implantation, all morphometric measurements became normal in the five investigated patients (Table 3, Figs. 3, 5).

Before shunt operation, the midsagittal area of the CC was reduced by 34% on average and the height and, to a lesser degree, the lengths of the CC were increased (Table 3). Twelve of 14 patients (except patients 6 and 7) showed pathological periventricular white matter changes before ventricular shunting. Figure 5 shows the mean values for the area, height and length of the CC of the normal subjects and patients before shunt operation and after ventricular drainage. In hydrocephalus the height and length of the CC were increased, while the cross-sectional area was reduced. In patients the mean height of the CC was 3.6, SD 0.6 cm (n=14; normal subjects, 2.5, SD 0.4, n=22, after Hofmann and collegues et [11], the length 7.8, SD 1.0 cm (normal, 7.1, SD 0.5 cm) and the area was 4.6 (0.8 cm^2 (normal, 7.0 (1.2 cm^2). The most pronounced changes in height and length of the CC were observed in communicating hydrocephalus (Fig. 5).

Discussion

In this study of patients with different types of hydrocephalus, the midsagittal area of the CC was found to be much reduced and its length and height increased. These changes reflect a thinning and elongation of the CC secondary to a pressure-induced rolling out [8, 17]. The most prominent changes were observed in patients with slowly progressive communicating hydrocephalus. The area of the CC was reduced in all investigated patients and amounted to 66% of the normal value, which was obtained with the same technique of measurements [11]. Similar findings were obtained with slighly different methods [13, 16, 24]. Eighty-six percent of the patients investigated with MRI in our study showed periventricular white matter changes before shunt operation. Such appearance of the periventricular white matter has been attributed to an axonal loss of callosal fibres [9], probably as a consequence of a reduced

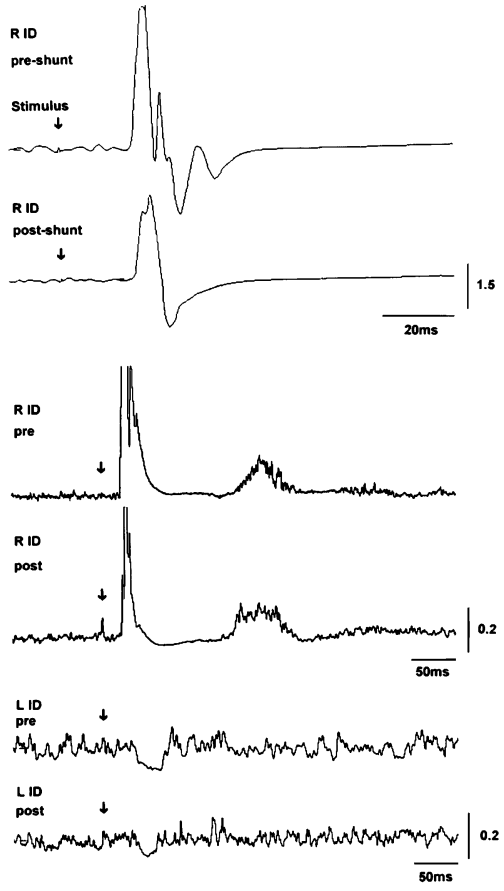

Fig. 2 Example of original EMG recordings of contralateral excitatory and ipsilateral inhibitory effects of transcranial magnetic motor cortex stimulation in patient 2 with hydrocephalus before (*pre-shunt*) and after (*post-shunt*) ventricular drainage. In contralateral muscles, shunting led to corticospinally mediated excitatory hand motor responses (*upper two traces*) with a reduced amplitude and number of late components (*traces 3 and 4*). In ipsilateral muscles the duration of transcallosal inhibition of EMG activity (*lower two traces*) became shorter. *Traces 3–6* are rectified and averages of 20 responses each. See stimulation conditions and response parameters in Fig. 1

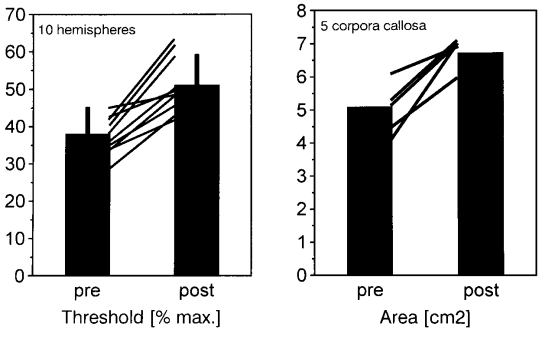

Fig. 3 Shunt-related changes of the cortical threshold for transcranially elicited corticospinally mediated hand motor responses (mean values and 1SD, individual threshold changes of ten hemispheres) and of the area of the corpus callosum (five brains). Measurements were made before (*pre*) and seven days after (*post*) ventricular drainage

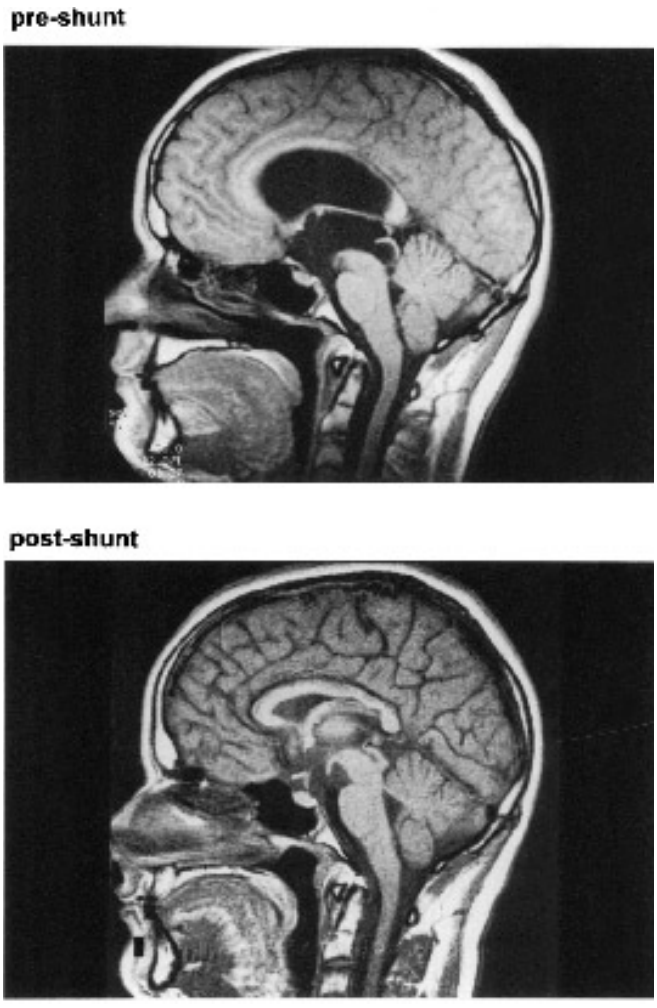

Fig. 4 Midsagittal T1-weighted MRI scans of the brain of patient 4 with hydrocephalus due to aquaeductal stenosis before (*pre-shunt*) and after (*post-shunt*) ventricular drainage (TR 480 ms/ TE 12 ms, 1.5 T). Shunt operation normalized the pressure-induced dilatation of the third and lateral ventricles, thinning of the corpus callosum and diminution of supratentorial sulci

number of capillaries, and thus reduced tissue perfusion [4]. Furthermore it is claimed that continuing ventricular dilatation causes an irreversible destruction of callosal fibres and may lead to permanent gliosis [27, 29]. However, Adams and Victor emphasize that the degree of fibre injury is “not to the extent that one might expect from the degree of compression” [2]. The normalization of the area and the deconvolution of the CC within 7 days after onset of ventricular drainage in all investigated patients exclude a pressure-induced atrophy of a significant number of callosal tract fibres and hint at a relaxation of the previously stretched and pulled callosal fibres. Our findings do not reveal the time course of the reconstitution of the gross brain anatomy which might have occurred already after 48–96 h of decompression [5, 27]. Short-term morphological changes cannot be investigated in man, since there is consent that a quick decompression of hydrocephalus should

Table 3 Height, length and area of the corpus callosum obtained by measurements on sagittal MRI-slices in patients with different types of hydrocephalus (*HO* obstructive, *HC* communicating, *NPH* normal-pressure hydrocephalus). In 5 patients, measurements were performed before and after shunt operation. (Means (1 SD)). Reference values after Hoffmann and collegues [11]

Subjects (*n*)	Normal subjects	Hydrocephalus patients					
		All	HO	HC	NPH	pre-shunt	post-shunt
	22	14	5	4	5	5	5
Height (cm)	2.5 (0.4)	3.6 (0.6)	3.2 (0.5)	4.4 (0.6)	3.4 (0.3)	3.3 (0.5)	2.5 (0.2)
Length (cm)	7.1 (0.5)	7.8 (1.0)	7.5 (0.6)	9.0 (1.1)	7.3 (0.4)	7.7 (0.7)	7.2 (0.2)
Area (cm^2)	7.0 (1.2)	4.6 (0.8)	5.2 (0.6)	4.3 (1.1)	4.3 (0.2)	5.0 (0.7)	6.7 (0.4)

be avoided to reduce the risk of intracranial bleeding or slit ventricle syndrome [2].

A large-scale fibre atrophy of callosal fibres due to hydrocephalus can also be excluded on the basis of this first systematic neurophysiological callosal "disconnection" test in man with TMS of the cortex, which did not reveal increased interhemispheric conduction times. The prolonged duration of TI hints at an increased dispersion of callosal excitation volleys. The simple approach of the investigation of transcallosal suppression of voluntary EMG activity in small hand muscles ipsilateral to cortex stimulation allows an assessment of the function of fibres connecting the primary motor cortex of both hemispheres [20] passing through the trunk of the CC [18, 19] which is roughly in accordance with anatomical studies in monkeys [22]. When the interhemispheric distances and the transcallosal conduction latency of, on average, 15 ms were taken into account, a callosal conduction velocity of about 10 m/s was calculated [18], which suggests an activation of large-diameter callosal fibres [32], which should theoretically be the fraction of callosal fibres most sensitive to pressure-induced lesions.

However, before ventricular drainage, an interhemispheric inhibition could be elicited in all patients. All parameters lay within normal range except the duration of TI, which was uni- or bilaterally prolonged in 73% of the 15 patients before and four of five patients after shunt operation. The persisting prolonged duration of TI even 7 days after decompression might reflect a continuing increased dispersion of callosal impulse conduction due to continuing oedema of periventricular white matter or that, despite restoration of the macroscopic anatomy, histological changes persist [26]. Even 7 days after shunt operation, persistent patchy areas of fluid accumulation are still to be seen scattered within the CC [27]. Furthermore, ependymal disruption and periventricular interstitial oedema were observable in cats after ventricular decompression at a stage in which the ventricles were already of normal volume and the cortex of normal thickness [27]. Shunt operation led to a significant increase in the onset latency of TI but which even then lay within normal range. This might

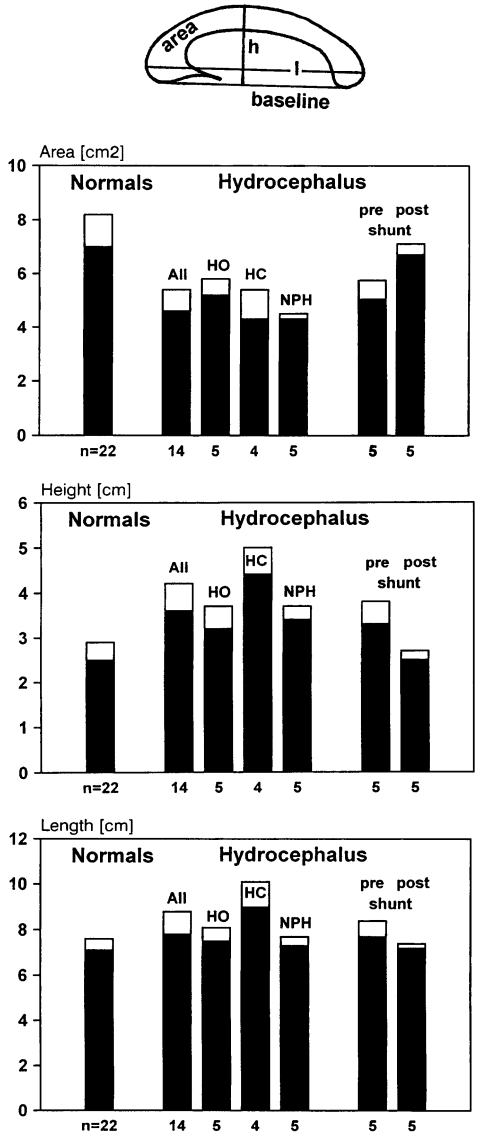

Fig. 5 Morphometric data of the area, height (*h*) and length (*l*) of the corpus callosum in 14 patients with occlusive (*HO*), communicating (*HC*), and normal pressure hydrocephalus (*NPH*). In five patients measurements (mean values of three consecutive measurements in each patient) were made before and after ventricular drainage (see also Fig. 5). Reference values were taken from another study using the same technique of morphometry [11]. (*black areas* mean values; *white areas* 1SD, see also Table 2)

be explained by the decrease in the brain size, which is paralleled by an increase in the distance between activated cortical neuronal structures and stimulation coil, which reduces the efficiency of TMS. In contrast to animal experiments [3, 27], the neurophysiological changes found in the function of callosal fibres were discrete in humans and exclude a loss or clear functional impairment of a substantial number of large-diameter callosal fibres interconnecting the primary motor cortices. In general, caution should be used when the results of experiments of hydrocephalic animals are related to findings in humans, since in the latter brain geometry and pressure conditions are different, the onset of the hydrocephalus is usually more insidious and patients are mostly seen in the stages of chronic change, as was also the case in our study.

Additionally, TMS of the motor cortex was used to assess the function of the corticospinal system but revealed no gross functional deficits in hydrocephalus. Especially, the central motor latencies were clearly normal and by this excluded a demyelination or loss of a significant number of descending fibres. The amplitudes of transcranially elicited hand motor responses lay within the normal range but were, on average, slightly smaller than in normal subjects, which might indicate a mild affect on the corticospinal fibres of the interstitial periventricular brain oedema, as was discussed above for the callosal fibres. Since in this study, for methodological reasons, cortical stimulation effects were investigated in hand muscles, the normal central motor latencies could be explained by the direction of the intraventricular pressure, which is probably exerted mainly on the most medial region of the corona radiata where the fibres from the cortical leg areas run and much less on fibres descending from the cortical hand motor representation. However, our own unpublished measurements of central motor latencies to leg muscles in patients with hydrocephalus have also revealed normal central motor latencies. Hence the impaired locomotion of the patients cannot clearly be related to an affect on fast-conducting [25] corticospinal connections, which are those being activated by TMS. Probably the motor disturbances in patients with hydrocephalus are due to an impairment of ipsilateral or callosally crossing connections between the basal ganglia and the primary [15] or premotor cortex rather than of efferents of the primary motor cortex. This assumption would be compatible with the finding of a disturbed pattern of EMG agonist and antagonist activation in patients with hydrocephalus and other disturbances of gait control similar to the condition in patients with Parkinson's disease [14, 31]. Interestingly, after ventricular drainage the response thresholds increased. As can be concluded from experiments in normal subjects simulating an increased distance between the magnetic stimulation coil and the motor cortex, the observed shunt-related increase in the thresholds for the activation of cortical excitatory and inhibitory neuronal elements might reflect a similar increase in the distance between cortex surface and coil after decompression. Furthermore the shunt-induced reduction of the water content [28] and the parallel decrease in electrical conductivity of the brain tissue might have led to a decrease in the transcranially induced electrical currents and thus have contributed to the increased excitation thresholds. Since the changes were paralleled by an improvement of gait and a normalization of the reflex level, the shunt-related threshold changes may serve as an ancillary indicator of morphological changes of the brain predicting successful ventricular decompression.

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