THE DIAGNOSIS AND TREATMENT OF HYDROCEPHALUS RESULTING FROM STRICTURES OF THE AQUEDUCT OF SYLVIUS

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Reprint from
SURGERY, GYNECOLOGY & OBSTETRICS
October, 1920, pages 340-358
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The purpose of this paper is to describe a type of hydrocephalus which occurs most frequently in infants, to give its pathology both gross and microscopical, to present the methods of diagnosis, and particularly to suggest a new form of treatment for this condition. To separate hydrocephalus into types is becoming increasingly difficult and, as our knowledge of this disease, but recently regarded as idiopathic, becomes better established, we are concerned less with subdividing it into groups and more with isolating the character and the exact location of the lesion which is causing the condition. Indeed, as the anatomy of the cerebrospinal spaces and the circulation of the cerebrospinal fluid become more clearly understood, hydrocephalus begins to appear as a single disease with varied anatomical manifestations, which are dependent upon the location of the underlying cause.

Hydrocephalus is always secondary to a primary cause and it should now be possible in every instance to locate the primary lesion, though its discovery, while at times simple, is usually sufficiently difficult to exhaust all the newer methods at our command. Moreover, in the chronic form of the disease (which is practically always referred to), there is but slight hope of spontaneous cure; there is no hope whatever from any medicinal therapy; the only hope lies in surgically correcting the cause of the disease, which is almost always an obstruction in the cerebrospinal spaces. The maximum results of surgical treatment, when this becomes proficient, and it is rapidly becoming so, will always be dependent on an early and accurate diagnosis.

The cases which comprise the particular group referred to in this paper are due to stenosis of the aqueduct of Sylvius. The vast majority of these cases begins in the prenatal period. The disease develops rapidly both during the prenatal and the postnatal life, though the manifestations may not be clearly evident for some time after birth. In 1914, I reported with Dr. Blackfan a series of 18 cases of hydrocephalus, and in 1917 a series of 25 cases, in which complete studies on the absorption of cerebrospinal fluid were made during life. Tests were devised to differentiate the types of hydrocephalus and other tests to obtain an index of the functions of the ventricles and the cerebrospinal spaces. The subdivision of most cases of hydrocephalus into two main classes, communicating and obstructive, still holds. In reality, nearly all cases of hydrocephalus are due to an obstruction, but in the so-called obstructive group the obstruction is in some part of the ventricular system. In the so-called communicating group, the ventricles are in communication with the subarachnoid space and the obstruction, usually adhesions, lies in the various parts of the subarachnoid space. The differentiation into these two great groups is clinically possible and easy of accomplishment by using a colored dye test. If, after injection of the dye into a lateral ventricle, it quickly appears in the spinal canal (lumbar puncture), there is communication between the ventricles and the subarachnoid space, and this type of hydrocephalus is known as "communicating." The absence of the dye in the spinal fluid denotes an obstruction at some point in the ventricular system; this type is called "obstructive." Obviously, this differentiation is of the utmost importance in determining the type of surgical treatment which is necessary.

From the later series of 25 cases, necropsy was obtained in 11; of this number, 4 were caused by obliteration of the aqueduct of Sylvius. Doubtless, several more had a similar lesion, but the absolute proof from necropsy was lacking.

Fourteen of the total number of cases in the series were shown by the dye test to be of the obstructive type and the remaining 11 to be of the communicating type. An analysis of the 14 cases of the obstructive type shows the relative incidence of those cases in which the obstruction was at the aqueduct of Sylvius. Necropsy was obtained in 8 of these 14 cases, and in half of them (4 cases) the aqueduct was occluded and, of course, this obstruction was the etiological factor in each instance, for the aqueduct cannot be occluded without hydrocephalus resulting. Two of these 8 cases were under observation during an attack of acute meningitis, and hydrocephalus was observed to follow this illness. In one case the meningitis was tuberculous, and in the other it was of influenza origin. Six cases remain of this obstructive group (of the 8 cases in which a postmortem examination was obtained), in which the hydrocephalus was of congenital origin: 4 of these had an obstruction at the aqueduct of Sylvius and 2 at the base of the brain (occluding the foramina of Magendie and Luschka by adhesions). This percentage (66 per cent) should, I think, express about a fair relative incidence of obstructions at the aqueduct of Sylvius in all cases of congenital hydrocephalus of the obstructive type. In other words, congenital occlusions at the aqueduct of Sylvius are probably at least twice as frequent as those at the foramina of Magendie and Luschka.

Since the publication of the above series, I have had 25 additional cases of hydrocephalus; 10 were of the communicating and 15 of the obstructive type. Postmortem examinations were obtained in 5 of the 10 cases of communicating hydrocephalus and, as in the previous series, the disease was caused by an inflammatory process which sealed the branches of the subarachnoid space, usually the cisternae. Necropsies were obtained in 5 of the 15 cases of obstructive hydrocephalus, and in each the obstruction was located at the aqueduct of Sylvius. In 3 additional recent cases of hydrocephalus which have been treated by operation, total occlusion at the aqueduct has been found in each instance. Undoubtedly, the same cause would be present in many of the re-
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Fig. 3. Sagittal view of the remains of a brain almost destroyed by the hydrocephalus. Note the obliterated aqueduct of Sylvius, the tremendous foramina of Monro which are indicated by the arrows. The cortex of the brain was of paper thinness and in many places completely absent. The contour of the brain is drawn. The fourth ventricle is normal, the cerebellum greatly compressed. Compare the destruction of brain in this case with that in Figure 2. The difference must be due to the time at which the obstruction of the aqueduct developed in intra-uterine life. The age of each case is approximately the same.

remaining 7 cases had a postmortem examination been made. In this series of 27 cases, 50 per cent of the autopsies and operations showed the aqueduct of Sylvius to be occluded (exactly the same percentage as in the other series). Stenosis of the aqueduct is, therefore, the causative lesion in about one-half of all cases of hydrocephalus occurring congenitally.

CASES OF STENOSIS OF THE AQUEDUCT OF SYLVIUS COLLECTED FROM THE LITERATURE

Magendie described an occlusion of the aqueduct of Sylvius in 1842; a marked dilatation of the lateral ventricles was also mentioned and discussed as having a probable relationship to the stricture, but this view was finally dismissed and the ventricular dilatation was regarded as incidental rather than causative.

Prior to Magendie's epoch-making publication, in which mention of the stricture of the iter was a mere incident, rational pathological descriptions were scarcely possible, for the normal was not known. Not until then was it known that the cavities in and around the brain contained fluid; Magendie discovered the foramen of Magendie, but even this opening is disputed to the present day. The foramina of Luschka were described several years later. Strictures of such a minute and apparently unimportant channel as the aqueduct of Sylvius could hardly have elicited any serious comment.

Oppenheim (1890) discovered a unique abnormality of the aqueduct at the necropsy of a patient who had suffered from a malady which had been diagnosed as myasthenia gravis during life. A thin bridge of tissue longitudinally bisected the iter (Fig. 5); in addition, numerous tiny nodules composed of lymphocytes protruded into the lumen of the aqueduct. The bisecting bridge had a very thin fibrous tissue center and was completely covered on either side by ependyma. There was no dilatation of the third or lateral ventricles, and in all probability the abnormality produced no injurious primary or secondary effects.


Fig. 4. Microscopical remnant of the aqueduct of Sylvius from the case shown in Figure 2. The surrounding tissue is glia.

Bourneville and Noir1 (1900) described a total occlusion of the iter, but, curiously, they placed no importance on the absence of this channel. Even tremendous enlargement of the third and both lateral ventricles of this case, contrasted to the normal small fourth ventricle, produced no impression on these authors who had the etiology of hydrocephalus in their hands but utterly failed to grasp it. They conclude, "Nothing whatever distinguishes this autopsy from that on any other case of hydrocephalus. Nevertheless we note the complete obliteration of the aqueduct of Sylvius which is not ordinarily present." Even at this recent date, the cause of hydrocephalus was not recognized! The most careful and painstaking postmortem examinations frequently revealed the correct pathological lesions, but they were dismissed because they conflicted with current whimsical theories. Even the great Moaro, nearly a century and a half ago, found several pathological specimens with mechanical obstructions in the ventricular system but, in his endeavor to prove the ventricles to be independent

1Bourneville and Noir. Le Progrés méd., 1900, July 14, p. 17.

of any communication with the exterior of the brain, discarded these findings as insignificant.

Touche2 records a most remarkable case of hydrocephalus which began with a series of convulsions when patient was 4 years of age. There was nothing in the history to indicate that the acute illness was or was not an inflammation, but the head began to enlarge shortly after this illness, prior to which the child had been perfectly normal. The patient lived to be 29 years old, at which time there was almost complete paralysis of both arms and legs, almost total lack of intelligence, and pronounced limitations of the extra-ocular movements. At autopsy, the third and both lateral ventricles were enormously dilated, the iter was completely occluded, and the fourth ventricle was not enlarged. Touche was the first among the references I have found who attributed the hydrocephalus to the obliteration of the aqueduct, though he does not discuss this relationship. No microscopic study of the mesencephalon was made.

Spiller3 (1902) reported two cases, each with a cicatrical stenosis of an interventricular passage, one at the foramen of Monro, the other at the aqueduct of Sylvius. He is the first to study the stricture microscopically and describes an hypertrophy of glia enclosing numerous minute rests of the epithelial lining of the aqueduct. The stenosis of the foramen of Monro (followed by unilateral hydrocephalus) was also due to a cicatrix. He thought both obstructions to be of inflammatory origin, pos-

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Fig. 6. Photograph of patient having partial occlusion of the aqueduct of Sylvius.

sibly tuberculous, and to be the cause of the hydrocephalus in each.

In an admirable article, Guthrie (1910) reported studies in hydrocephalus from a large series of postmortem examinations of patients who died of meningitis or its sequelae. His views on the relationship of meningitis to the production of hydrocephalus were most sane and on the whole far in advance of contemporary articles on hydrocephalus. He emphasizes a relationship of diseases which is certainly correct and all-important, but one which is even now poorly recognized. Eight cases of complete occlusion of the iter were included in his report; in 6, the occlusion was undoubtedly inflammatory and occurred during the progress of the meningitis. In 2 cases of hydrocephalus (which alone of his series are included in this report of cases collected from the literature), there was neither a history nor any postmortem evidence of meningitis, but the aqueduct of Sylvius was totally occluded in each. The possible relationship of meningitis to the formation of these strictures, as implied by Guthrie, will be discussed later.

Schlapp and Gere (1911) presented a series of 4 cases, each having complete occlusion of the iter; later (1917) the number was increased to seven. All of these cases were carefully studied microscopically.

1 Guthrie, L. S. Practitioner, 1910, lxxv, 47.

An additional case is not included here because the obstruction at the aqueduct was due to a tumor. The symptoms, incidence and treatment of such lesions are entirely different and will be considered subsequently.

PATHOLOGY OF STRICTURES OF THE AQUEDUCT

All of these cases, including the 3 entered by Blackfan and myself, have essentially the same microscopic pathology which was described by Spiller. In each instance, only epithelial remnants of the lining ependyma remain, and an hypertrophy of the glial tissue replaces the defect. In one of our cases, not a trace of epithelium could be found in any of the sections, but the other 2 which were so examined had microscopic tubular remains of ependyma; but no possible channel could be reconstructed from the third to the fourth ventricle through this connective tissue.

In the gross, the region of the occluded iter differs but little from the surrounding mesencephalic tissue. There is usually no increased density noticeable to the touch and one gets the impression of a normal mesencephalon minus the aqueduct. In one of our cases, however, the region of the aqueduct appeared fairly sharply circumscribed, almost like a tumor; it was much harder and more fibrous but microscopically the picture was similar to that of the others.

In 4 of our 7 cases, the entire length of the aqueduct was occluded. In 1, the stricture was not quite complete (Fig. 8), though phenolsulphonephthalein did not appear in the spinal fluid within a half hour after it had been injected into the lateral ventricle, as it normally should when the aqueduct is patent. In one case, the stricture was a very thin diaphragm which transmitted light and should easily have been amenable to treatment. In another case, there were two obstructions in the ventricular system, one at the iter, the second at the base of the brain (Figs. 9 and 10). The fourth ventricle, which intervened between the strictures, was markedly dilated as should be expected from failure of its fluid to escape into the cisterna magna. The stricture at the aqueduct was only about 3 millimeters in length. Apparently one of Guthrie's cases, also, had two such obstructions and at the same locations, for the fourth ventricle was enlarged, a finding which could not occur unless both foramina of Luschka together with the foramen of

1 Dandy and Blackfan. Loc. cit.
<table>
<thead>
<tr>
<th>Author</th>
<th>Age of Patient</th>
<th>Time of Onset of Symptoms</th>
<th>Antecedent or Other Illness</th>
<th>Signs and Symptoms</th>
<th>Gross Pathology</th>
<th>Microscopic Pathology</th>
<th>General Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Oppenheim</td>
<td>Adult</td>
<td></td>
<td></td>
<td>Treated as bulbar paralysis</td>
<td>Bridge across aqueduct</td>
<td>Hypertrophy of glia. Numerous small nodules</td>
<td>No symptoms of intracranial pressure because obstruction slight, if any</td>
</tr>
<tr>
<td>2 Bournville and Noir</td>
<td>9 years</td>
<td>At 6 months or before</td>
<td>Mother had smallpox—premature delivery</td>
<td>Epilepsy Spasticity Sexual precocity</td>
<td>No trace of aqueduct</td>
<td></td>
<td>Child always weak. No intelligence. Somatic development not unusual. Marked sexual precocity. Lays no emphasis on occlusion of aqueduct</td>
</tr>
<tr>
<td>3 Touche</td>
<td>20 years</td>
<td>At 4 years</td>
<td>Convulsions for 2 months</td>
<td>Large head. Absence of mentality. Bilateral paralysis almost complete. Partial ophtalmoplegia</td>
<td>Aqueduct occluded completely. Third and both lateral ventricles large. Fourth normal size</td>
<td>None</td>
<td>Patient lived 25 years after hydrocephalus was evident</td>
</tr>
<tr>
<td>4 Spiller</td>
<td>19</td>
<td>Doubtful</td>
<td></td>
<td>Difficulty in walking Staggering dizziness</td>
<td>Aqueduct closed third and lateral ventricles. Fourth normal</td>
<td>Tiny opening microscopically Neuropilis increased Ependymal cells in groups</td>
<td>Headaches since childhood</td>
</tr>
<tr>
<td>5 Guthrie</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No trace of aqueduct</td>
<td></td>
<td>Fourth ventricle small</td>
</tr>
<tr>
<td>6 Guthrie</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No trace of aqueduct</td>
<td></td>
<td>Fourth ventricle also dilated. No evidence of meningitis at necroscopy</td>
</tr>
<tr>
<td>7 Dandy and Blackfan</td>
<td>6 months</td>
<td>Noticed at birth</td>
<td>None</td>
<td>Large head, circumference 40 centimeters Arms and legs spastic</td>
<td>Total occlusion of aqueduct. Small pouch at third ventricle</td>
<td>Microscopic remnants of aqueduct. Hypertrophy of glia</td>
<td>Myelomeningocele also present. Third and both lateral ventricles large</td>
</tr>
<tr>
<td>8 Dandy and Blackfan</td>
<td>6 weeks</td>
<td>Large head at birth</td>
<td>None</td>
<td>Large head, circumference 50 centimeters Convolusions began second week. Extra-ocular palsies, nystagmus</td>
<td>Cerebral hemispheres almost completely destroyed. Aqueduct completely occluded</td>
<td>No microscopic remnants of aqueduct. Increased production of glia</td>
<td>Very advanced. Total occlusion must have existed early in intra-uterine life. Fourth ventricle mere slit. Third and both lateral ventricles extremely large</td>
</tr>
<tr>
<td>9 Dandy and Blackfan</td>
<td>5 years</td>
<td>Head large at birth Abnormal at 4-5 months Never able to hold up head</td>
<td>None</td>
<td>Head 54 centimeters; grew to 72 centimeters. Strabismus Spasticity of arms and legs Wassermann negative</td>
<td>Double obstruction (1) Aqueduct Sylvius (2) Foramina of Luschka and Magendie</td>
<td></td>
<td>Patient was observed 5 years. Some development of speech and slight intelligence despite progress of disease. Hydronephrosis (unilateral) due to a congenital obstruction of the urethra</td>
</tr>
<tr>
<td>Case</td>
<td>Age 1</td>
<td>Age 2</td>
<td>Diagnosis 1</td>
<td>Diagnosis 2</td>
<td>Symptoms</td>
<td>Treatment</td>
<td>Outcome</td>
</tr>
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<tr>
<td>10</td>
<td>Schlapp and Gere</td>
<td>3-1/2 years</td>
<td>Head large at birth</td>
<td>Fall when 3-1/2 years old</td>
<td>Unsteady gait, irritability, headache, convulsions, no extra-ocular palsies, Coughed disc, No ataxia, Slight nystagmus</td>
<td>Head 62 centimeters</td>
<td>Complete occlusion of aqueduct: Tiny cysts</td>
</tr>
<tr>
<td>11</td>
<td>Schlapp and Gere</td>
<td>5-1/2 months</td>
<td>Head large at birth, unsteady gait, irritability</td>
<td>Instrumental delivery</td>
<td>Convulsions, Head 63 centimeters, Limbs spastic, Knee kicks active</td>
<td>Complete closure of aqueduct</td>
<td>Increase in glia</td>
</tr>
<tr>
<td>12</td>
<td>Schlapp and Gere</td>
<td>2-1/2 years</td>
<td>Head large at birth, gradually increased</td>
<td>None mentioned</td>
<td>Head 67 centimeters, Never able to move arms or legs, Probably blind or deaf, Cortex 1/2 centimeters, Ventricles large, Aqueduct entirely closed</td>
<td>Hypertrophy of glia</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Schlapp and Gere</td>
<td>6 months</td>
<td>Large since birth</td>
<td>One eye turned out since birth, Blind bilateral ankleclonus and Babinski</td>
<td>Head 10-1/2 centimeters, Tumor of fourth ventricle</td>
<td>Hypertrophy of glia with cyst formation entire length of aqueduct</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Schlapp and Gere</td>
<td>15 months</td>
<td></td>
<td></td>
<td></td>
<td>Cellular reaction around aqueduct which is closed</td>
<td>Evidence of syphilis</td>
</tr>
<tr>
<td>15</td>
<td>Schlapp and Gere</td>
<td>6 months</td>
<td>Birth</td>
<td>Before birth</td>
<td></td>
<td>Aqueduct closed</td>
<td>Increase of glia, Small slit open microscopically</td>
</tr>
<tr>
<td>16</td>
<td>Schlapp and Gere</td>
<td>Birth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Dandy</td>
<td>2 months</td>
<td>1-1/2 months</td>
<td>None</td>
<td>Head 40.5 centimeters</td>
<td>Tiny opening of aqueduct remains</td>
<td>Increased glia</td>
</tr>
<tr>
<td>18</td>
<td>Dandy</td>
<td>4 months</td>
<td>Head large at birth</td>
<td>Easy labor</td>
<td>Head 58 centimeters, Slight strabismus, Child died of pneumonia, No operation</td>
<td>Thin band across aqueduct</td>
<td>None made</td>
</tr>
<tr>
<td>19</td>
<td>Dandy</td>
<td>3 months</td>
<td>Head large at birth</td>
<td>Easy labor, Head noticed to be large at age of 6 weeks</td>
<td>Head 30.5 centimeters</td>
<td>Total occlusion of aqueduct</td>
<td>None made</td>
</tr>
<tr>
<td>20</td>
<td>Dandy</td>
<td>3 months</td>
<td>Head large at birth</td>
<td></td>
<td>Head 48.75 centimeters, One month later was 53.75 centimeters</td>
<td>Total occlusion of aqueduct</td>
<td>None made</td>
</tr>
</tbody>
</table>

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Magendie were closed. In 2 of the cases described by Schlapp and Gere, only the posterior end of the aqueduct was occluded, the anterior part being dilated up to the point of the stricture. This was also true in one of our specimens.

It is hardly necessary to note that in every case in which the aqueduct of Sylvius is occluded, the third and both lateral ventricles are dilated, the degree varying with the time which has lapsed after the stricture has formed. The size of the fourth ventricle is not increased except in those rare cases in which the foramina of Luschka and Magendie are also occluded (Figs. 9 and 10); it is usually, though not invariably, smaller than normal because of the superimposed pressure of the hydrocephalic ventricles (Figs. 2 and 3), although this pressure is greatly reduced by the comparatively inelastic tentorium cerebelli which holds the heavy cerebral hemispheres. The reason the third and both lateral ventricles dilate is because the closure of the aqueduct of Sylvius removes the only avenue by which the cerebrospinal fluid can escape from these ventricles. And, since there is only a trivial amount of absorption through the walls of the ventricles and a constant formation of fluid within the ventricles from the choroid plexus, the ventricles must continue to enlarge. To compensate for this enlargement, the brain is steadily destroyed. In most of the cases included in this series and reported by various authors the ventricles had reached extreme dilatation and the amount of cerebral cortex which remained was small. In 2 of our cases, there was only a film of brain remaining and this was attached to the leptomeninges; and in many areas of considerable size the brain tissue was entirely absent.

By the newer methods, it is now possible to determine the presence of hydrocephalus in the earlier stages of its development. It is no longer necessary to await progressive enlargement of the head with the great destruction of brain tissue. In one of our cases, the hydrocephalus was suspected at birth on account of the presence of a myelomeningocele and of an unusually large anterior fontanelle.

The presence of a meningocele should always be looked upon as a suspicious sign that hydrocephalus may be an accompanying condition which may be far more serious than the meningocele. The cause of the frequent association of hydrocephalus and meningocele is as yet not entirely clear, but the importance and frequency of the relationship cannot be overestimated.
THE CAUSE OF STRicture OF THE AQUEDUCT

During early embryonic development, the aqueduct of Sylvius shows no differentiation from the remainder of the neural tube. Everywhere the entire neural canal, including the aqueduct of Sylvius, therefore, must necessarily have been patent and lined by epithelium. It is easy to understand how the foramina of Luschka and Magendie may be impermeable, simply because they have failed to develop, because they are secondary openings from a primary closed neural tube; but no such hypothesis is tenable in explaining stenosis of the aqueduct of Sylvius. Since, therefore, the aqueduct of Sylvius is primarily an open tube, its closure must be secondary and never due to agenesis. The presence of microscopic epithelial (Fig. 4) remains and occasionally of a minute patent channel, evident at times even macroscopically, serve as supporting evidence that the iter has been in existence but has been subsequently occluded by some abnormal process.

The aqueduct is the weakest and at the same time the most important link in the ventricular system. Its lumen should normally be open for the passage of cerebrospinal fluid which is constantly but very slowly being poured through it. The hypertrophy of glia cannot be regarded as a tumor because it has not the cellular element of a tumor; moreover, it does not proliferate beyond the immediate region of the iter.

Glia behaves essentially as does connective tissue. Its growth must be secondary and not primary. It would be difficult to imagine a primary rampant growth of connective tissue beyond the confines of a normal epithelial lining. It would appear more probable that a primary destruction of the epithelial lining of the aqueduct had resulted and the natural attempt of nature to heal the breach by glial tissue had resulted in the stenosis of the iter at the affected zone. Such an hypothesis, and of course more it cannot be, is supported by the method of formation of stenoses elsewhere in the body, either by trauma plus infection, or even by infection alone. The closure of only a portion of the aqueduct in many cases supports the view that an epithelial defect is primary, for a primary connective-tissue growth would hardly be so restricted.

We know that intracranial intra-uterine inflammations do exist, because adhesions are so frequently found over the surface of the brain. We have no information by which it is possible to decide whether these inflammatory changes are the result of bacteria or merely
toxins, but this differentiation is irrelevant. There is every reason why the aqueduct of Sylvius should be most susceptible to any such intra-uterine inflammatory changes. Its relatively great length, together with its tiny caliber, makes it a place of least resistance both to trauma and to inflammatory changes or to both; and it is easily conceivable that only a relatively slight injury to the aqueduct, either by trauma or by toxins, would be necessary to produce sufficient destruction of the epithelium to result in a stricture—which could scarcely be reparable by any method of nature.

In this connection, there are several findings in the above series of cases which are important. Oppenheim’s case was characterized by a number of small nodules which protruded into the lumen and which were made up of clusters of lymphocytes. Similar lymphocytic changes, which have been interpreted as inflammatory by the authors, were described by Schlapp and Gere in two of their cases. In all of our cases, and doubtless most of the others which are recorded here, the process is too old to record any cellular inflammatory reaction, had such changes been present at the time of onset of the lesion. It is not necessary to relegate all possible inflammatory changes to the overcrowded and underreasoned syphilitic category, for there must be many types of mild inflammatory changes of which we know very little at the present time. Guthrie’s observations bear the greatest weight in this connection. He found in postmortem examinations of a series of patients who had died of meningitis, 8 instances in which total occlusion of the aqueduct had resulted from the inflammations. In all of his cases, the meningitis was post-
Fig. r3. Ventriculogram from a case of hydrocephalus diagnosed at birth. The ventriculogram shows the third ventricle filled with air in addition to one lateral ventricle. There is no air in the fourth ventricle. The obstruction is therefore at the aqueduct of Sylvius.

Undoubtedly, the aqueduct is much more resistant to injury after birth and becomes progressively more so; this statement is made upon the relative infrequency of stenosis of the aqueduct with increasing age. If, therefore, inflammations can occlude the aqueduct so frequently after birth, a relatively trivial infection or irritant would doubtless produce the same disastrous results in the tender period of intra-uterine life.

ANALYSIS OF THE CLINICAL MANIFESTATIONS IN THIS SERIES

A large head of varying size is the only constant feature of these cases and, obviously, the large head is a manifestation of all types of hydrocephalus and not of obstructions of the aqueduct in particular. The size of the head is only very roughly proportional to the size of the lateral ventricles. At birth the head may be only slightly enlarged or, as usually happens, may attract no attention whatever and still the ventricles may be several times the normal size. Any appreciable enlargement of the head means a very great enlargement of the ventricles and a corresponding amount of destruction of brain tissue. The size of the head is, therefore, only a very rough index of the condition of the contents of the cranial chamber; the small head is a very poor index, if any at all; the large head is a very good index. After the first few years of life, the size of the head changes but slightly despite great enlargement of the ventricles, because the united bones preclude much separation. We have made several diagnoses of early hydrocephalus soon after birth by carefully examining the anterior fontanelle for enlargement, fulness, and alteration of shape. Not infrequently the anterior and posterior fontanelles are continuous, owing to separation of the interparietal suture. The anterior fontanelle will also usually project farther forward than normal and farther lateralward by separation of the interfrontal and frontoparietal sutures respectively.

It is quite remarkable how a limited amount of intelligence may continue to develop in young children in spite of the rapid progressive destruction of the brain. Even with an enormous head, measuring 60 to 70 centimeters in circumference (Figs. 9 and 10), the child may learn to speak distinctly though, of course, with a greatly restricted vocabulary. A considerable amount of destruction of the brain may be tolerated in the early stages of hydrocephalus without any or with only moderate mental inferiority; this holds true only so far, after which the mental changes progress rapidly and, of course, are irreparable.

Many hydrocephalic children have a downward displacement of the eyes due to depression of the roof of the orbit. Owing to this displacement, the sclera shows above the iris and the iris is partially covered below. Quite frequently there is also a considerable limitation of the various extra-ocular movements. This is usually symmetrical, though one set of muscles may be more involved in one eye than the other. I believe these palsies are due, not to implication of the quadrigeminal bodies as could be readily inferred from the close proximity of these bodies to the iter, but rather to the pressure of the bulging, distended third ventricle which presses upon the third, fourth, and sixth nerves directly. Were the affection in the quadrigeminal bodies or in the nuclei of the third nerves which are located in the mesencephalon, the
extra-ocular palsy would be complete rather than partial.

Convulsions are not uncommonly present, though probably the majority of patients are not so afflicted, or have only an occasional attack; the attacks are general and may be both petit mal and grand mal. Their explanation is still obscure because of our meager knowledge of the underlying cause. Spasticity of the arms and legs is also frequent, doubtless from pressure of the intraventricular fluid on the thinning pyramidal tract. Eventually, this destruction leads to complete paralysis of the arms and legs.

Blindness is not infrequent, even when the head can enlarge quite readily. The optic nerves are directly compressed by the distended third ventricle which thus produces the loss of vision. Ankle clonus, Babinski and Oppenheim reflexes are present with varying frequency. The reflexes are usually exaggerated, in keeping with the degree of spasticity. One might expect to find a choked disc constantly, but most cases have a primary atrophy instead; the explanation for this fact is that the third ventricle acts as a tumor and presses on the optic chiasm directly, thus occluding the space in the sheath of the nerves.

But all of these signs and symptoms are not present in every case or even type of hydrocephalus. They are the manifestations of hydrocephalus, and have no direct bearing upon the primary lesion in the aqueduct of Sylvius or elsewhere. Moreover, there is no sign or symptom which is characteristic of a stricture of the aqueduct of Sylvius as such. A tumor in the mid-brain blocking the aqueduct of Sylvius has signs which are pathognomonic, but only because the contiguous nuclei or the quadrigeminal bodies are involved. Were the hypertrophied glia a progressive lesion, it would likewise involve these contiguous structures and produce the same signs but, being restricted, only the signs of pressure are usually present.

**CASE WITH TWO OBSTRUCTIONS, ONE AT THE AQUEDUCT OF SYLVIUS, THE OTHER AT THE FORAMINA OF LUSCHKA AND MAGENDIE.**

This patient was 5 years old at the time of his death. He had been under observation from time to time for 4 1/2 years, during which time the size of his head steadily increased. The patient was the third of five children, the others being hearty and well. There is no history of tuberculosis or syphilis in the family. The birth was at full term and the delivery not abnormal though more difficult than the others. When one month old, the patient had two "inward spasms"; the head was thrown back and the eyes rolled up; these spells were apparently convulsions and never reappeared. There has never been a history of meningitis. When 3 months old, it was definitely agreed that his head was abnormally large. Before this time, however, the neighbors had commented on the "large round head." When 4 1/2 years old, he had "screaming spells" almost daily, but these were not associated with convulsions or vomiting. At this time, the family physician made the diagnosis of water on the brain. Feeding was uneventful and he thrived and his body grew normally. He was never able to hold up his head, to sit up or to walk. When a year old, it was noticed that his left arm was weaker than the right. The fontanelles remained open and wide. When 9 months old, the anterior fontanelle measured 11 centimeters transversely and 9 centimeters anteroposteriorly. The posterior fontanelle was closed. Two years later (2 1/2 years old) the fontanelle measured 10 by 9.75 centimeters. The head measurements at various intervals are as follows:

- When 6 1/2 months old, 52.5 centimeters.
- When 9 months old, 54.0 centimeters.
- When 13 months old, 56.0 centimeters.
- When 14 months old, 57.0 centimeters.
- When 15 months old, 57.8 centimeters (puncture of corpus callosum done 1 month ago).
- When 23 months old, 62.0 centimeters.
- When 29 months old, 64.0 centimeters.
- When 33 months old, 65.0 centimeters.
- When 60 months old, 68.0 centimeters (at time of death).

This happens to be the first case of hydrocephalus in which the absorption from the ventricles and the subarachnoid space was tested by the phenolsulphonephthalein test. It was found that the dye appeared in the urine 55 minutes after injection into the ventricle and in 2 hours following the appearance time only 0.5 per cent was excreted by the kidneys which were shown to have a normal function. Spinal punctures, repeatedly made, yielded only 2 to 3 cubic centimeters of clear fluid, containing none of the phenolsulphonephthalein, thereby demonstrating the absence of communication between the ventricles and the subarachnoid space. When phthalein was injected into the ventricles, a normal absorption, 35 per cent in 2 hours, was obtained. The cause of the hydrocephalus is evident from these studies. An obstruction was indicated and, because of the very small amount of fluid obtained at lumbar puncture, the obstruction was thought to be at the foramina of Luschka and Magendie. These observations were made before the institution of surgical treatment was advisable.
Fig. 14. This and the succeeding drawings by Miss Norris show the operative procedure, in which the stricture of the aqueduct of Sylvius is opened and enlarged and the tube inserted to maintain the opening. In this figure the wound is shown. The occipital muscles are separated in the mid-line and the bone exposed. A ventricular puncture is made to reduce the intracranial pressure.

A puncture of the corpus callosum was made when the child was 14 months old, but no beneficial results were obtained. The child died when 5 years old of bilateral pyonephrosis which was caused by a congenital urethral stricture. The foramina of Magendie and Luschka were occluded but the surprising finding was the second obstruction at the aqueduct of Sylvius (Figs. 9 and 10). The third ventricle and particularly the lateral ventricles were tremendously distended. The fourth ventricle was moderately distended.

Had the obstruction been solely at the aqueduct of Sylvius, the size of the fourth ventricle would not have been increased and, conversely with an obstruction at the aqueduct, the fourth ventricle could dilate only when the foramina of Luschka and Magendie are obstructed.

CASE OF PARTIAL BUT NEARLY TOTAL OCCLUSION OF THE AQUEDUCT OF SYLVIUS

Patient was first seen when 6 weeks old. It was apparent at that time from the large fontanelle that hydrocephalus was present though the size of the head was normal, and no abnormality of the head had been suspected by the parents. In 2 weeks, the circumference of the head increased 3 centimeters and then measured 39 centimeters. A meningocele had been partially excised 2 days after birth, and the patient was brought to me to complete the excision of the meningocele. The wound had healed and no nerve palsies had followed. The sagittal suture was open, uniting the anterior and posterior fontanelles.

A ventriculogram shows a large lateral ventricle, at least four times the normal size, leaving a greatly
reduced cortex. On spinal puncture, only 5 cubic centimeters of fluid were obtained and indigo-carminine, which had been injected into the lateral ventricle, did not appear in the spinal fluid in 35 minutes. Unfortunately, a puncture was not made 1 hour after the injection, for a trace of fluid might have been present at that time. This inference is made because at autopsy the aqueduct was reduced to a channel of filiform size. It was really still a partial obstruction though nearly complete, and sufficiently complete to cause the high grade hydrocephalus. The foramina of Luschka and Magendie were patent and of normal size. The third and both lateral ventricles were greatly dilated, the fourth ventricle was very small. Undoubtedly, this is a progressive lesion and shortly the lumen would have been completely closed as in the other cases.

DIAGNOSIS OF A STRicture OF THE AQUEDUCT OF SYLVius

An occlusion of the aqueduct of Sylvius can now be accurately localized. It is first necessary to prove the existence of hydrocephalus; second, to find whether it is of the obstructive or of the communicating type; and finally, if obstructive, to locate the obstruction. Unfortunately, hydrocephalus is now usually diagnosed only in the late or relatively late stages of the disease by the characteristic enlargement of the head; at this stage, the diagnosis is just as easily made by the parent as by the physician. Moreover, when any considerable enlargement of the head is present, the destruction of the brain is so great that the practical value of the diagnosis is relatively slight, for any effective treatment would leave the patient mentally deficient.

In the early stages of hydrocephalus in children, and in all cases after union of the sutures, the diagnosis of hydrocephalus is extremely difficult. But the important time to make a diagnosis is at the beginning of the disease, before the large head has made the diagnosis unquestioned. It is not within the scope of this paper to deal with this most important phase of hydrocephalus—the early diagnosis—but it should always be eagerly borne in mind and when suspected, the patient should be referred to a competent authority to ascertain definitely whether or not this condition is present. This diagnosis can now be made with absolute certainty and the degree of the ventricular dilatation determined with absolute accuracy by ventriculography (Fig. 13), and when moderately advanced, not infrequently the condition can be recognized by an X-ray without ventriculography. Without these methods, the determination of the presence or absence of hydrocephalus in the early stages is entirely guesswork, that is until the tell-tale growth of the head has taken place. Careful weekly measurement of the head should always be made until any suspicion of hydrocephalus is allayed or verified. When the diagnosis of hydrocephalus is made, the proper treatment, which depends entirely upon the type of hydrocephalus, should be instituted without delay.

When the diagnosis of hydrocephalus has been made, a simple and safe procedure will determine whether the ventricles communicate with the subarachnoid space and thus determine into which of the two great groups—obstructive hydrocephalus or communicat-
ing hydrocephalus—the particular case belongs. One cubic centimeter of indigo-carmine (or of a carefully neutralized solution of phenolsulphonephthalein, though I have ceased to use this in the ventricles because of an occasional reaction) should be injected into a lateral ventricle and 30 minutes later a lumbar puncture made. If the ventricles communicate with the subarachnoid space, the color will have appeared in quantity in the spinal fluid by this time or very shortly thereafter. The hydrocephalus would, therefore, be of the communicating type and one could be certain that there was no obstruction in any part of the ventricular system. For the purposes of this paper it would exclude any occlusion of the aqueduct of Sylvius.

On the other hand, if the dye does not appear in the spinal fluid in this allotted period of time, one could know just as positively that an obstruction existed at some part of the ventricular system; it might be at the foramen of Monro—a rare possibility—or more probably either (1) at the aqueduct of Sylvius or (2) at the basal foramina of Magendie and Luschka (all three must be occluded to produce hydrocephalus). In cases of congenital hydrocephalus, as indicated by statistics given at the beginning of the paper, the chances are about two to one that the obstruction is at the aqueduct of Sylvius, and about one to two that the foramina of Magendie and Luschka are occluded. There are some rarer exceptions to these
interpretations which need not be considered here.

The precise location of the site of the obstruction can be accomplished only by ventriculography.\(^1\) If the obstruction is at the aqueduct of Sylvius, the shadow of the third and particularly of the lateral ventricles will be shown to be greatly dilated, but no air will be present in the fourth ventricle. If air is in the fourth ventricle, the obstruction cannot be at the aqueduct of Sylvius. Further differentiation of the types of hydrocephalus by air injections will be considered in greater detail in a paper which will appear shortly. The absence of a shadow of the fourth ventricle must not be taken as conclusive evidence of an occlusion at the iter unless one is confident of a perfect and complete injection, that is one which has almost completely filled both lateral ventricles and in which the head has been properly manipulated in order to permit the air to pass into and remain in the fourth ventricle.

**AN OPERATIVE TREATMENT FOR STRICTURES OF THE AQUEUDCT OF SYLVIUS**

The difficulties encountered in treating lesions of the aqueduct of Sylvius would appear almost insuperable, but I have been encouraged to the possibilities of a direct attack upon the mesencephalon even in infants by the increasing number of cases in which the aqueduct has been exposed during the extirpation of cerebellar tumors. At least 25 times during the past year it has been possible to watch the cerebrospinal fluid pour through the aqueduct (often enlarged by the hydrocephalus which follows tumors) into the fourth ventricle. On two occasions, a pineal tumor has been exposed and in several instances the exposure of tumors of the anterior part of the vermis or the removal of huge tumors of the cerebellum left this structure in full view. In animals long tedious operations for removal of the pineal body were borne with impunity even when the puppy operated upon was only 3 or 4 days old.

In dogs I have found that an obstruction could be placed in the aqueduct and produce hydrocephalus;\(^2\) later, it could be removed and the hydrocephalus cured. Moreover, an accumulated past experience with the surgical treatment of hydrocephalus would seem to indicate strongly that the treatment of hydrocephalus must be directed toward an attack on the cause of the disease. All efforts at circumventing the cause, such as a puncture of the corpus callosum, or puncture of the wall of a lateral ventricle, are doomed to failure because of anatomical and physio-

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logical factors which must be recognized but which have been disregarded or not known in the empirical treatments instituted heretofore. It seems impossible to produce an opening in the third ventricle which will drain the cerebrospinal fluid into an absorbing area except by way of the normal route into the fourth ventricle. It is necessary that cerebrospinal fluid pass into the cisternae before it can be distributed into the finer radicles of the subarachnoid space, for it is only there that an adequate absorption of the fluid is possible. The fluid can only reach the cisterna magna by way of the fourth ventricle through the foramina of Luschka and Magendie, and the fourth ventricle can only be reached through the aqueduct of Sylvius. Following a puncture of the corpus callosum, the cerebrospinal fluid passes into the subdural space in which absorption is no greater than in the ventricle from which the fluid escaped. Moreover, the opening in the roof of the ventricle remains patent for a brief period only. All small openings through any considerable thickness of brain tissue must cicatrize unless lined by epithelium and, pending closure of the opening, the fluid which escapes becomes encysted unless it is poured into an absorbing area.

In an attempt to treat the cause directly, I propose a method of reconstructing the obliterated aqueduct of Sylvius. In probably the majority of cases which are collected here, the entire aqueduct is obliterated by a very dense fibrous scar. It is hardly to be expected that any new channel as long as the iter can be permanently maintained after reconstruction, when the entire aqueduct is involved. But in those cases where only a small portion of the aqueduct is occluded, and ideally perhaps where the aqueduct is crossed by a thin diaphragm, or where the obstruction is only partial, a restoration of the iter should appear to be a hopeful possibility.

The operation has been performed twice, on children 1 year and 5 years of age. There was very little reaction to the operation in either case. The older child died 7 weeks later of pneumonia; the younger child is still living. There is, of course, no way that the operator can tell beforehand the longitudinal extent of the obstruction in the iter. It is thus necessary to subject all, in whom the intellectual indications are favorable, to the operation, without which there is not the slightest chance of improvement.

Should there be any doubt as to the site of the obstruction, the absolute decision can be made at the operation without delay or difficulty. After eliminating a foramen of Monro obstruction, by proving communication between the two lateral ventricles, there are only two other possible locations for the occlusion—the foramina of Magendie and...
Luschka, and the aqueduct of Sylvius. Fortunately, the same incision is made for the treatment of either lesion. Patency or occlusion of the foramen of Magendie can readily be determined by an operator of experience. The patency or occlusion of the foramina of Luschka is of less importance, for one foramen is adequate to permit egress of all the cerebrospinal fluid. If the foramen of Magendie is patent, the occlusion, by elimination, must be at the aqueduct of Sylvius. On the other hand, 2 cases of double stricture in this series, one at the aqueduct, the other at the foramen of Magendie, emphasize the danger of assuming that the aqueduct is patent after the occlusion of the foramen of Magendie has been relieved. The indigo-carmine test will precisely determine this point.

The steps in the operation are shown in the accompanying drawings (Figs. 14 to 18). After a bilateral exposure of the cerebellum (Fig. 14), the vermis is elevated with a small spatula (Fig. 15), exposing a normal foramen of Magendie and fourth ventricle. Into this a fine catheter is gently passed forward until it is met by the obstruction at the aqueduct of Sylvius. To get a satisfactory exposure it is necessary to divide the lower half of the vermis in the mid-line and carry this incision through the roof of the fourth ventricle (Figs. 15 and 16). A nasal dilator introduced into this defect (Fig. 16) permits a good exposure of the funnel-like anterior terminus of the fourth ventricle and the entrance to the aqueduct of Sylvius. A small sound entering this orifice meets the obstruction and is carefully forced through it into the third ventricle (Fig. 17). Fluid at once freely escapes through the opening which again establishes communication between the third and fourth ventricles. Larger sounds are then passed to increase the size of the lumen. A small rubber catheter is pushed into the newly made channel (Fig. 18) and left in position for a period of 2 to 3 weeks after the operation. The tube is perforated in numerous places to prevent closure of the lumen by fibrin. The walls of that part of the tube which lies in the aqueduct are smooth and are without perforations. The anterior part of the tube projects into the third ventricle, the posterior part is in the fourth ventricle and lies on the pons and medulla. It is anchored with a silk ligature to the dura at the foramen magnum. The end of the tube is cut off at this point and the lumen closed by a ligature. The excess tube which traverses the entire length of the fourth ventricle is necessary to preclude the possibility of the tube becoming dislocated and lost. The nuchal muscles are carefully closed over the wound, giving a good protection of tissues over the large foreign body which is quite deeply buried and is free from skin infections during its abode in the brain.

Such a big foreign body is necessarily accompanied by a reaction of considerable severity which ultimately necessitates its removal at a second operation. I have endeavored to leave the tube in place as long as possible, hoping for epithelization of the iter, and thereby preservation of lumen after the tube has been removed. In one case which died, the tube was left in place 2 weeks, and in the second case it remained 3 weeks. The reaction of the patient to the tube is evident as a general lethargy, loss of appetite, vomiting, loss of weight, temperature elevation, and a full and tight anterior fontanelle, in other words, the manifestations of general intracranial pressure. Signs of pressure quickly disappear after the tube is removed.

It will doubtless seem a radical procedure to hemisect or even partially hemisect the vermis of the cerebellum. I have three patients who are perfectly well after complete removal of the vermis and part of both lobes of the cerebellum, the operations being necessary to remove large tumors. They have no effects of this complete section. In other cases, partial section of the vermis has been necessary and has been devoid of any apparent ill effects. Certainly, it is necessary to see every step in remaking the aqueduct. Inferiorly, the pyramidal tract and the nuclei of the third nerve are so near and, above, the vein of Galen is in such intimate contact that a false passage will obviously have serious results. Moreover, an attempt to pass a sound blindly by palpation could scarcely be successful.
In the surviving patient in which the tube was inserted into the aqueduct there are no disturbances. It is now over a year since the operation. His movements are entirely without ataxia. He can hold up his head and walk with no sign of staggering gait or loss of equilibrium. He is talking both English and Norwegian quite freely but it is too soon to predict the final outcome.

SUMMARY AND CONCLUSIONS

1. Cicatricial stenosis of the aqueduct of Sylvius is the most frequent lesion in congenital hydrocephalus (about 50 per cent), and is found in a large percentage of cases of hydrocephalus occurring in infancy and early childhood. It may occur (though rarely) in adult life.

2. Hydrocephalus always follows occlusion of the aqueduct. The third and both lateral ventricles progressively dilate. The fourth ventricle, being posterior to the obstruction, does not enlarge.

3. In the gross, the occluded aqueduct appears to be replaced by a fibrous tissue which microscopically is neuroglia. Microscopic remnants of the aqueduct are usually but not invariably found.

4. The stenosis may occupy the entire length of the aqueduct, or varying parts; it may be only a thin even transparent membrane. Again, the stricture may be only partial.

5. Strictures of the aqueduct of Sylvius can be diagnosed and accurately localized. The indigo-carmine test will indicate that an obstruction is present; ventriculography will be the means of precisely locating the obstruction.

6. Spontaneous relief is not possible. Surgical attempts to drain the fluid from the third ventricle to the exterior of the brain have all proved futile. The openings invariably close and the fluid cannot absorb in the subdural space.

7. A surgical procedure is suggested which is directed toward the cause. A new aqueduct of Sylvius is constructed; a tube is left in place for 2 to 3 weeks. It is hoped the epithelium will regenerate and establish a new canal.

8. This operation has been performed on 2 cases, both recovering from the operation. One patient died of pneumonia several weeks later, the second seems well 1 year after the operation.