Mechanical dysfunction of ventriculoperitoneal shunts caused by calcification of the silicone rubber catheter

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Object. The authors studied new and calcified shunt catheters to identify the prevalence of failures caused by aging materials in the shunt. Complications associated with these devices have various origins. Among late complications, fracture or migration of the system is related to the subcutaneous adhesion of the distal tubing in a growing child. A review of a cohort of 64 children who underwent shunt placement in 1980 with barium-impregnated distal catheters showed that 10 of these patients underwent reoperation for complications related to aging of the shunt material. This group represents 15% of the whole series and 30% of those children who were followed for more than 3 years. The true impact of aging of materials on shunt function is probably underestimated.

Methods. The authors performed physical, chemical, and mechanical analyses of the retrieved aged catheters and also of new catheters, resulting in the following findings: 1) calcifications were observed only on the external surface of the catheter, predominantly in its subcutaneous segment at the level of the neck and anterior chest wall; 2) calcifications contained particles of free silicon and barium sulfate, signifying fragmentation of the polymer; 3) the microstructure of the silicone polymer was modified: microfractures and alteration of the polymeric network were observed; 4) silanol groups were observed on the external surface of the catheter; and 5) the mechanical properties of the silicone rubber were degraded, and the aged catheters were more brittle than the new ones, with ruptures at elongations and fracture energy much lower than that seen in new catheters.

Furthermore, in vitro testing with a metastable solution of simulated body fluid demonstrated the critical impact of pH variations in liquid media and surface degradation of the catheters on the precipitation of hydroxyapatite crystals.

Conclusions. Although most shunt complications can be addressed by better patient management and surgical technique, late complications appear to be partly related to aging of the material. Distal tubing calcifications have been observed in barium-impregnated catheters. The industry recently responded to these observations by introducing plain silicone-coated shunt tubing; further evaluation will show what improvement can be expected.

Key Words • shunt dysfunction • cerebrospinal fluid • shunt • calcification • hydrocephalus • silicone rubber

Despite improvements in materials, devices, and surgical technique, numerous problems and complications are still encountered in shunt surgery. From reviews of large series of treated hydrocephalic patients, two main types of complications can be distinguished, early and late. Early complications in the 1st year after shunt insertion relate to overall patient management, the surgical technique used in shunt insertion, and the functioning of the shunt device itself. Late shunt complications relate almost exclusively to proximal obstruction and problems associated with aging of the shunt material. Catheters become calcified, rigid, and fragile, promoting subcutaneous attachment. Consequently, they will migrate or break during the patient’s growth.

Little research has been conducted so far to identify the pathophysiological mechanisms related to aging of the material of ventriculoperitoneal (VP) shunts. The long-term importance of this problem is likely to become more prominent, because progress in other fields of treatment has led to improved survival rates and quality of life for these patients.

In the present work, the phenomenon of aging of shunt material was studied in a series of children with hydrocephalus who were treated sufficiently early to allow long-term follow-up assessment.

Clinical Material and Methods

Clinical Study

This study included 64 children (36 boys and 28 girls) who had undergone insertion of their initial VP shunt at the Department of Pediatric Neurosurgery of Hôpital Necker-Enfants Malades, in Paris, France between January 1 and December 31, 1980. Patients who had undergone previous shunt revisions or exchange of preexisting materials with new ones were excluded. Three of the 64 patients had previously undergone an unsuccessful at-
Si-NMR. The...HCO$_3$- as a complexing agent. Ca$^{2+}$ was conducted on SO$_2$+ caustic soda solution at HPO$_4$K$^+$ 4- temperature, with a deformation rate of 500 mm/min machine; MTS Systems Corp., Eden Prairie, MN) at room catheters were compared using tensile tests (MTS-810 deformation behaviors of new and used (calcified) shunt system. Excluding children who died or were graphs were obtained to assess the mechanical integrity of shunt placement, plain skull, chest, and abdominal radiographs were obtained until stability in brain computerized tomography scans until stability in assessment and evaluation of intelligence and development ed. Routine assessment included neuropsychological assessment depending on the underlying disease, usually at 2 and 6 months postoperatively and then yearly for the next 5 years and every 2 to 3 years after that if no problems existed. Routine assessment included neuropsychological assessment and evaluation of intelligence and development quotients. Radiological follow up included two or three brain computerized tomography scans until stability in ventricular size was observed, with other scans as necessary according to clinical indications. At 5 years after shunt placement, plain skull, chest, and abdominal radiographs were obtained to assess the mechanical integrity of the shunt system. Excluding children who died or were lost to follow-up review, 48 patients were followed for a mean of 9.8 years (range 1–16 years).

Experimental Study

An experimental laboratory study$^{20}$ was conducted on the catheters removed during shunt revision and also on new, unused catheters. The tests included mechanical measurements and physicochemical studies.

Mechanical Properties of Catheters. The load-versus-deformation behaviors of new and used (calcified) catheters were compared using tensile tests (MTS-810 machine; MTS Systems Corp., Eden Prairie, MN) at room temperature, with a deformation rate of 500 mm/min$^{-1}$, in agreement with standard NFT 46002, Norme Française pour la Traction.

The new catheters were of two kinds: Type A was a striped catheter that was transparent with a white line and contained a band of barium compound in its internal surface with a 1.1-mm internal diameter and a 2.3-mm external diameter; and Type B was a barium sulfate–impregnated catheter, all white and of the same dimensions as the striped catheters. Five samples were tested for each type of new catheter. The used catheters were all Type B. Four samples were tested, two with low calcification and two with high calcification.

Physicochemical Study. Scanning electron microscopy was used to observe the catheters and quantitative micro-analysis was completed by means of x-ray emission. The calcified materials were characterized by x-ray diffraction, Raman spectroscopy and microscopy, and Magic Angle Spinning–nuclear magnetic resonance (MAS-NMR) of silicon-29. The polymer itself was subjected to physicochemical analysis, allowing determination of reticulation rate, barium content, and silanol groups.

The in vitro study of calcification was aimed at investigating the influence of the presence of a catheter on the precipitation of calcium salts in saturated solutions, because of chemical parameters (in particular, presence of silanol groups) or physical parameters (in particular, presence of liquid–solid interfaces). Moreover, the role of the surface degradation of a catheter was a point of interest. As seen in Table 2, in vitro tests were conducted using a metastable aqueous solution of simulated body fluid to simulate extracellular fluid. The pH was buffered at 7.4 with hydrochloric acid mixed with tri(hydroxymethyl)amino methane, and the temperature was maintained at 37°C.

The tests were conducted in the absence or presence of a catheter, either new or “damaged.” The used catheters retrieved from patients were too calcified and their surfaces too rough to enable useful information to be elicited on the early stages of calcification, which we assumed to be the most critical. Consequently, “damaged” catheters were prepared through chemical degradation by soaking them for 24 hours in a 30 g/L$^{-1}$ caustic soda solution at 100°C. The extent of degradation was estimated using ultraviolet and Raman spectroscopy and $^{29}$Si-NMR. The precipitation of calcium was followed using ethylenediamine tetraacetic acid Na, as a complexing agent.

Results

Clinical Study

Shunt Dysfunctions in the Whole Series. During the follow-up period, 29 children (45%) had shunt problems requiring revisions of part of the system. These problems are summarized in Table 3. Thirteen children died of var-

### Table 1

<table>
<thead>
<tr>
<th>Cause</th>
<th>No. of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>aqueductal stenosis</td>
<td>5</td>
</tr>
<tr>
<td>postmeningitis</td>
<td>6</td>
</tr>
<tr>
<td>hemorrhage</td>
<td>6</td>
</tr>
<tr>
<td>dysraphism</td>
<td>9</td>
</tr>
<tr>
<td>Dandy–Walker syndrome</td>
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</tr>
<tr>
<td>craniosynostosis</td>
<td>6</td>
</tr>
<tr>
<td>congenital toxoplasmosis</td>
<td>3</td>
</tr>
<tr>
<td>cerebral atrophy</td>
<td>2</td>
</tr>
<tr>
<td>arachnoid cyst of 3rd ventricle</td>
<td>1</td>
</tr>
<tr>
<td>tumor</td>
<td>14</td>
</tr>
<tr>
<td>unknown</td>
<td>11</td>
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</table>

### Table 2

<table>
<thead>
<tr>
<th>Ion Concentration (mmol/L)</th>
<th>Solution</th>
<th>pH</th>
<th>Na$^+$</th>
<th>K$^+$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
<th>Cl$^-$</th>
<th>HCO$_3^-$</th>
<th>HPO$_4^-$</th>
<th>SO$_4^{2-}$</th>
</tr>
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<tr>
<td>ECF</td>
<td>7.4</td>
<td>142</td>
<td>5</td>
<td>2.5</td>
<td>1.5</td>
<td>103</td>
<td>27</td>
<td>1</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>SBF</td>
<td>7.4</td>
<td>142</td>
<td>5</td>
<td>2.5</td>
<td>1.5</td>
<td>148</td>
<td>4.2</td>
<td>1.0</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

* ECF = extracellular fluid; SBF = simulated body fluid.
Calcification of ventriculoperitoneal shunt catheters

ious causes. In six cases (9%), death was directly related to the operation (infection in five, acute intracranial hypertension in one) and in seven cases it was related to the underlying cause of the hydrocephalus (tumor progression, vascular malformation, or encephalitis).

The group of 10 patients with late mechanical dysfunction were the focus of this study, because complications in these patients included rupture of material or disconnection, which were potentially attributable to aging of the shunt material. Table 4 summarizes the clinical information for these patients.

Analysis of Late Mechanical Dysfunction. Critical analysis of the 10 patients with mechanical dysfunction suspected to have been caused by aging of the shunt material, in comparison with the group of patients who had other complications, revealed several interesting points. First, the mean age at the time of implantation was younger in the group of patients with late mechanical dysfunction (mean 4 months, standard deviation [SD] 3.7 months), compared with the group who had other types of shunt problems (mean 28 months, SD 26.8 months).

Second, the interval between insertion of the VP shunt and its revision was different in the two groups. The mechanical complications caused by fracture or migration, possibly related to material aging, were all late, occurring at a mean interval of 90 months after implantation (range 35–188 months, SD 53.5 months). In contrast, other types of shunt malfunction, consisting of infections or obstructions, occurred soon after implantation, after a mean interval of 11 months (range 0–108 months, SD 25 months).

Third, the follow-up duration was different in the two groups. The children with mechanical complications suspected to have been caused by material aging were followed for more than 5 years, a mean of 12 years, compared with the mean of 6 years in the other group of patients. The real incidence of late fractures or migration is probably underestimated. Although it has been observed in 10 (15.6%) of the 64 patients studied, if only the cases followed for more than 5 years, a mean of 12 years, compared with the mean of 6 years in the other group of patients. The real incidence of late fractures or migration is probably underestimated. Although it has been observed in 10 (15.6%) of the 64 patients studied, if only the cases followed for more than 5 years, a mean of 12 years, compared with the mean of 6 years in the other group of patients.

The two groups showed a highly significant difference (p < 0.01) for the three studied parameters (age at shunt insertion, follow-up interval, and follow-up duration).

Experimental Study

Mechanical Properties of Catheters. Figure 1 shows examples of tensile-test graphs registered using four samples cut from a new catheter of the striped variety (Type A). The vertical (y) axis represents the load (F) and the horizontal (x) axis represents elongation: λ = L/λ - 2 where λ = L/L₀, L being length under load and L₀ initial length. For λ values that are not too high (that is, below approximately 500%) the curves F compared with λ - λ - 2 and λ - λ - 2 are markedly linear, which indicates that the materials obey the sigmoidal trend that is typical of rubber elasticity, that is F = E (λ - λ - 2) where E is the stiffness coefficient.

Elongation was observed to be reversible up to approximately 500%, whereas at higher elongation values, hardening develops, which results in partially irreversible changes in the catheter. Type A and B catheters exhibit almost the same characteristics. They can undergo very great deformation, with fracture elongation always in excess of 1000%, which was the practical limit of the tensile machine. In fact, such high deformations far exceed surgical needs.

In comparison with new catheters, calcified catheters exhibit a dramatic loss of mechanical properties. Indeed, the four samples broke at low elongation values of 200%, 250%, 270%, and 310%, respectively, with the two lowest values found, as expected, for the two samples with the highest calcification. This confirms the loss of ductility that is associated with calcification, as observed qualita-

### Table 3

<table>
<thead>
<tr>
<th>Cause</th>
<th>No. of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>infection</td>
<td>8</td>
</tr>
<tr>
<td>protrusion of distal catheter through the anus</td>
<td>1</td>
</tr>
<tr>
<td>obstruction of catheter or valve</td>
<td>7</td>
</tr>
<tr>
<td>replacement of peritoneal catheter</td>
<td>4</td>
</tr>
<tr>
<td>early migration (in the 1st 6 mos)</td>
<td>2</td>
</tr>
<tr>
<td>subdural fluid collection</td>
<td>3</td>
</tr>
<tr>
<td>mechanical dysfunction due to late fracture, migration, or disconnection</td>
<td>10</td>
</tr>
</tbody>
</table>

* Valves not fixed to the galea.

### Table 4

Clinical profile of 10 children with late mechanical VP shunt complications

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Origin of Hydrocephalus</th>
<th>Sex</th>
<th>Age at Implantation</th>
<th>Age at Revision</th>
<th>Duration of Implantation</th>
<th>Type of Dysfunction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>unknown</td>
<td>M</td>
<td>9 mos /28 mos*</td>
<td>57 mos</td>
<td>29 mos</td>
<td>disconnection of ventricular catheter</td>
</tr>
<tr>
<td>2</td>
<td>thoracic meningocoele</td>
<td>M</td>
<td>4 days</td>
<td>112 mos</td>
<td>112 mos</td>
<td>migration</td>
</tr>
<tr>
<td>3</td>
<td>congenital toxoplasmosis</td>
<td>M</td>
<td>6 mos</td>
<td>194 mos</td>
<td>188 mos</td>
<td>disconnection of ventricular catheter</td>
</tr>
<tr>
<td>4</td>
<td>intraventricular hemorrhage</td>
<td>M</td>
<td>7 mos /17 mos*</td>
<td>65 mos</td>
<td>48 mos</td>
<td>disconnection of distal catheter</td>
</tr>
<tr>
<td>5</td>
<td>arachnoid cyst of rt lat ventricle</td>
<td>M</td>
<td>2 mos</td>
<td>44 mos</td>
<td>42 mos</td>
<td>fracture of valve body</td>
</tr>
<tr>
<td>6</td>
<td>pneumococcal meningitis</td>
<td>M</td>
<td>7 mos</td>
<td>43 mos</td>
<td>36 mos</td>
<td>fracture of catheter at patient’s neck</td>
</tr>
<tr>
<td>7</td>
<td>aqueductal stenosis</td>
<td>M</td>
<td>2.5 mos</td>
<td>125 mos</td>
<td>122.5 mos</td>
<td>disconnection of ventricular catheter</td>
</tr>
<tr>
<td>8</td>
<td>lumbar diastenatomyelia</td>
<td>M</td>
<td>13 days</td>
<td>57 mos</td>
<td>56.5 mos</td>
<td>migration</td>
</tr>
<tr>
<td>9</td>
<td>occipital encephalocoele</td>
<td>F</td>
<td>13 days</td>
<td>144 mos</td>
<td>143.5 mos</td>
<td>migration</td>
</tr>
<tr>
<td>10</td>
<td>cerebral contusion</td>
<td>F</td>
<td>5 mos</td>
<td>150 mos</td>
<td>145 mos</td>
<td>disconnection of distal catheter</td>
</tr>
</tbody>
</table>

* First shunt removed for infection; second shunt inserted for delayed psychomotor development.
† First shunt emerged through the anus; second shunt inserted for delayed psychomotor development.
tively when manipulating new and used catheters. An increase in stiffness is associated with the loss of elongation. However, it was not worth trying to quantify this increase, which is caused mainly by the calcified coating composed of hydroxylapatite, a crystallized mineral phase whose stiffness is much higher than that of silicone.

Analysis of Calcified Catheters. On macroscopic examination, the catheters that had been in place for a long time and were retrieved during revision surgery appeared to be covered with a film of irregular, hardened, pale tissue, similar to calcification (Fig. 2). This film had developed only on the external surface of the catheter, whereas the lumen remained normal and patent. The complex structure of the calcified catheter was considerably more rigid and fragile than the new devices. The irregular and uneven nature of the outer wall explains the subcutaneous adherence that was always encountered perioperatively during removal of shunt tubing. This calcification was restricted to the part located subcutaneously and was not found in the part of the tube situated inside the peritoneal cavity or intracranially. The calcified catheter was encased in a dense fibrous reaction zone that had created a "fibrous tunnel," completely isolating the catheter from subcutaneous tissues. This fibrous reaction zone was densely adherent to the calcification of the tube. Therefore, it was almost impossible to remove the catheter during surgery.

Using the techniques outlined earlier, we made detailed observations of calcified catheters that demonstrated the following (Fig. 3).

The mineral fraction of the calcification is mainly constituted of hydroxylapatite of varying degrees of crystallization (\(\text{Ca}_{10}[\text{PO}_4]_6[\text{OH}]_2\)). This formula corresponds to the pure and stoichiometric crystal, but in most cases the stoichiometry was disturbed by cationic or anionic substitutions.

The calcifications contained small amounts of silicon and barium sulfate. It was assumed that the polymer of which the catheter was made had "liberated" a portion of its contents. This hypothesis was confirmed by using microanalysis. Working at the limit of precision of this technique, it was found that the superficial layers of the catheter wall had an approximate loss of 1% of silicon and 3% of barium.

The superficial zones of the polymer were modified. They exhibited microscopic cracks and structural irregularities. The polymeric network had been altered; calcium and phosphorus had migrated deeper into the polymer, more than several micrometers. The polymer was therefore degraded, with centrifugal diffusion of elements relevant to the calcification.

The thickness of the mineralized layer had been increased by the rate of deposition of silanol groups (SiOH= hydrolyzed groups), present at the surface of the polymer. These hydrolyzed groups were testimony to the breakdown of chains inside the polymer, another confirmation of the degradation of the material.

In Vitro Calcification. Ultraviolet and Raman spectroscopy and \(^{29}\text{Si-NMR}\) showed the presence of silanol groups.
on the degraded catheter surface and therefore confirmed that the polymeric network of the silicone had been partially broken by chemical degradation.

In tests conducted in the absence of catheters, the pH played a very important role in the precipitation kinetics of calcium phosphate; a small increase in pH leads to a strong destabilization of the solution. For example, 10 days at pH 7.4 do not provoke any precipitation, whereas at pH 7.5 the precipitation is marked and at pH 7.7 it becomes massive.

In tests conducted in the presence of chemically degraded catheters, the devices favor precipitation of hydroxylapatite, although quantification of the effect is difficult. Such a phenomenon was expected, because the presence of any interface in a saturated solution helps heterogeneous nucleation. Moreover, the chemically degraded catheters were more efficient than the nondegraded ones, which indicates that chemical factors (probably the silanol groups) enhance precipitation. For catheters in their normal, biological environment, surface degradation can be caused by chemical and biological factors (for example, the action of macrophages) as well as mechanical factors (that is, compression–dilation stress in areas frequently used for shunt insertion, such as the patient’s neck or chest wall).

**Discussion**

**Shunt Dysfunction Caused by Aging of the Material: the Importance of the Problem**

Aging and degradation of shunt material should be kept in mind when treating hydrocephalic patients, because these phenomena will continue to be present regardless of any other advances in shunt design. It is difficult to determine the true frequency of these problems from a review of the literature. As we demonstrate in our series, prolonged clinical observation is necessary. The patients are often lost to follow up. Dysfunction from other causes (infection or obstruction) necessitates an exchange of material, which reduces the real duration of implantation and subsequent aging of shunt material.

In a large series of 1719 children with hydrocephalus who were treated and who received follow-up care for a period of 10 years, the actuarial risk of shunt dysfunction at the end of the study was estimated to be 70%. During the 1st postoperative year, 30% of the shunts were revised and the subsequent risk was 2 to 5% per year. Obstruction was the most frequent cause (56%), followed by fracture, disconnection, and late migration, which accounted for 19% of mechanical complications occurring in 13% of the children. It must be noted that these complications occurred later in comparison with other causes of shunt revision (at a mean of 5 years). Taking into account these results and our own observations, it is probable that some series reported in the literature underestimate the true incidence of complications related to aging of the shunt material, because of short follow-up times, or in some instances, because they do not include all types of complications such as late migrations. Other observations reported in the literature resemble ours with respect to the clinical presentation and the mode of aging of shunt material. In these series, the catheters had been in place for long periods (> 5 years), all patients were children, and shunt degradation had been responsible in the majority of cases for the fracture or disconnection.

Fig. 2. Photograph showing macroscopic view of a calcified shunt.

Fig. 3. Electron micrographs showing the superficial zone of a calcified catheter. A: The external surface is covered with calcification, but the lumen remains smooth. Original magnification × 35. B: The calcification has penetrated the polymer. Original magnification × 75.
Mechanism of Calcification

The calcification of implantable prostheses made of silicone has been studied extensively in cardiac patients. The presence of a fibrous tunnel encasing the tubing explains why although fractured, the shunt system occasionally remains functional. Because of the fibrous tunnel in such cases, cerebrospinal fluid (CSF) cannot escape from the fractured tube and reaches the distal end of the shunt and the peritoneal cavity. For this reason, caution should be exercised when the physician is faced with a clinically well patient and evidence of fractured tubing on the plain radiographs, because the shunt could still be functioning and essential to the patient.

Degradation of Catheters

The calcified catheters are rigid and fragile, a condition mainly stemming from the characteristics of the calcified sheet that covers them but also from catheter degradation itself. Indeed, deterioration of the mechanical properties of the catheter can be caused by alterations of its superficial zone. The reticulation damage that has been observed both by ourselves and Echizenya, et al., seems to be an important factor in this alteration. According to Kronenthal, the biopolymers deteriorate in four ways: 1) the structure is altered by hydration; 2) some covalent bonds of the chains are weakened; 3) these bonds are broken, which reduces the molecular weight of the polymer; and 4) certain soluble fragments are digested by macrophages. The effects of temperature, irradiation, and chemical reactions on intra- and interchain links can contribute to the degradation of elastomers. In the human body, the silicones are not subjected to extreme temperatures or irradiation but they have to resist chemical and mechanical insults for a number of years.

Corrosion. Variable biochemical corrosion effects, depending on the environment in which the catheter is immersed, are indicated by the presence of calcification only in the catheters that are placed in subcutaneous or vascular areas (catheter degradation is also seen in ventriculostomy shunts). The cerebral parenchyma and the peritoneal cavity do not degrade silicone catheters. We believe that this differential action of the surrounding environment depends on cellular reaction or immune mechanisms, and therefore is present in areas in which migration of immunocompetent cells can occur, although this does not explain the lack of calcification in the peritoneal cavity.

Some authors have reported delayed inflammatory reaction in the track of catheters, regardless of the presence of infection. The signs of local inflammatory reaction were associated with formation of a T-cell granuloma, indicating cell-mediated immunity. Humoral immunity was also invoked; immunoglobulin G antibodies that were specifically directed against silicone (Silastic) were present in the serum of two patients reported on by Goldblum, et al. In the report by Heggers, et al., the inflammatory reaction was said to be related to release of silicon particles from the aging silicone, resulting from an “attack” by macrophages. These particles were regarded as irritants and potentially responsible for a chronic inflammatory reaction. This reaction was predominantly a foreign body giant cell granuloma type. However, it is still debatable whether this reaction is caused by free silicon itself or other particles that were added inadvertently during implantation, such as cotton fibers, talc granules, and hair.

From studies conducted on the distribution of cells around subcutaneously implanted elastomers in animals, Zhao, et
Calcification of ventriculoperitoneal shunt catheters

al. concluded that the formation of giant cells from fusion of macrophages is responsible for degradation of the material. Aging of the silicone tubing located outside of the subcutaneous tissue follows a different course. There is no cellular immunity in the cerebral parenchyma, and ventricular catheters do not induce a gliotic reaction inside the brain parenchyma, as judged by the absence of adherent cells on the silicone. To our knowledge, apart from the reaction of the peritoneal cavity to the presence of a foreign body (poor absorption of CSF and formation of pseudocysts) the specific reaction of the peritoneum to silicone has not been studied.

Mechanical Stress. Similarly to chemical insults, mechanical forces applied during movement can break certain interatomic links and help form others. Therefore, it is possible to explain the preferential degradation of catheters, which is observed in sites at which strong biological activity (rich vascularization) coincides with mechanical deformation. In prosthetic heart valves, this is observed in the mobile parts that are subjected to intense mechanical stress. In VP shunts this is observed at the level of the neck, a segment that is placed in extreme hyperextension and contralateral rotation during shunt implantation. Several reports have indicated that the most common site of shunt fracture was 2 to 4 cm above the clavicle. Elisevitch, et al., identified three zones of reduced resistance: 1) the connection between the distal catheter and reservoir or valve; 2) the point of traversing the galea; and 3) the crossing of the clavicle.

Role of the Host Environment

Considering the variety of adverse reactions and insults that the catheters are subjected to after implantation, calcification and fracture are not the most important events determining the long-term function of VP shunts. Because a number of shunts exhibit a very long life span, it appears that there is a great interindividual variation with respect to aging of silicone material. The age of the patient is clearly a determining factor for implant calcification. The younger the patient the greater the tendency for shunt calcification from physiological or pathological causes. This is well established in cardiac surgery, in which youth of the patient is a contraindication for placement of bioprosthetic cardiac valves. This greater tendency for calcification appears to be connected to the relative elevation of serum phosphorus in children compared with adults. In the case of shunts placed in children, there is the additional late mechanical stress applied during growth, when mechanical traction is applied to the catheter, which is fixed in the subcutaneous tissues. The distal tubing thus immobilized by calcification cannot slide; therefore, the profile of the valve will allow it to migrate down, the distal catheter will fracture later, or the elements will disconnect at junction sites. Actually, late fracture of the distal catheter or migration of the shunt is observed only in children. In a review of mechanical shunt dysfunctions in 289 adults, Decq, et al., found only seven migrations, which they did not specify as early or late, and no distal fracture or disconnection.

Choice of Material and Technique of Implantation

The surgeon implanting a VP shunt has little choice of material: the catheters are all made of a peroxide-treated silicone (Silastic), with no platinum curing treatment. In catheters entirely impregnated with barium, extrusion of gross particles could leave holes on the surface of the polymer, promoting hydroxyapatite formation, which indicates that Type A catheters are preferable.

On the other hand, a variety of valves are commercially available, which differ in the way they regulate CSF dynamics and also in the way they are manufactured. For the purpose of this study, the mechanism of CSF pressure control is of no interest, but the profile of the valve is of relevance to the late mechanical complications. A tubular valve in the catheter line, such as the Hakim (Cordis Neuro), the Codman Unishunt (Codman, Randolph, MA), and the Holter valve (Codman), has a tendency to migrate because it is pulled by a fixed calcified catheter in a growing child. The round-bodied valves (Orbis-Sigma; Elekta, Paris, France, or PS Medical, Coleta, CA), cannot migrate distally despite the traction. In these cases, disconnection or fracture of the distal catheter will result from the traction applied to the aging degraded material, and the stress exceeds the mechanical strength of the material. By avoiding any distal connectors, we try to facilitate sliding of the distal catheter. Although this additional precaution increases the life of shunt systems by avoiding early fractures, it does not avoid the spontaneous fixation of the catheter in the subcutaneous tissues that is caused by calcification. If this fixation takes place before the patient stops growing, there is an increased risk of fracture or migration. Likewise, the one-piece systems cannot be disconnected; therefore, they break when subjected to the aforementioned forces.

Is there any difference between ventriculoatrial and VP shunts with respect to the problem of material aging? In the study by Langmoen, et al., in which 2065 shunts were examined, the authors suggest there is no difference. Among 1298 ventriculoatrial shunts, a distal catheter fracture was seen in 38 cases (2.9%) and in 715 VP shunts fracture was observed in 22 cases (3%).

Conclusions

Taking all causes into consideration, mechanical dysfunction of ventricular shunts leads to considerable patient morbidity and mortality. The psychological impact of the risk of complications associated with the valve and subsequent reoperations is evident in both children and their families. Moreover, the socioeconomic cost of revisions is substantial.

Is the prevention of late complications from ventricular shunts an “impossible dream”? Although the early complications related to patient management and shunt insertion techniques are preventable to a large extent, factors related to aging of the shunt material are beyond the surgeon’s control. It remains debatable whether detection of calcification along the catheter track in routine chest radiographs should prompt replacement of material in growing children.

Improvements in shunt longevity will be dictated by research in biomaterials and their changes following implantation for long periods. One possibility could be to manufacture catheters with a modified surface that is more resistant to the various forms of stress and less prone to...
amplify the effects. The industry recently responded to these observations by developing plain silicone-coated shunt tubing. Evaluation of these modified materials will show what improvements to expect.

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