Mineralization and biodegradation of CSF shunting systems

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The mineralization and biodegradation of cerebrospinal fluid shunting systems were studied using material from 25 shunts that had been implanted for between 6 days and 10 years. New unused materials were also examined for comparison. Surface changes in six systems could be observed under an operating microscope. Substantial quantities of a white deposit had adhered to the tubing in four of the shunts. These changes were most advanced in the galeal penetrative portion of the shunts and are believed to have been caused by mechanical stress. Scanning electron microscopic analysis revealed surface wrinkles, microscopic holes, and tiny particles, suggesting deterioration of the material itself. An energy-dispersive analysis using x-rays demonstrated that the surface deposits were due to mineralization of calcium phosphate and that the tiny particle growth was aluminum. These changes may be a consequence of the degradation of silicone rubber. A discriminant analysis of the mineralization was carried out; thus, the age of the host and the duration of system implantation could be correlated with the incidence of mineralization (p < 0.1). A measurement of the physical properties showed progressive change with a remarkable deterioration in systems implanted for more than 5 years.

KEY WORDS  shunt  mineralogical study  biodegradation  silicone rubber

Early in the 1950's, silicones were introduced as materials suitable for implantation. At about that time, silicones were used for the manufacture of cerebrospinal fluid (CSF) shunting systems in neurosurgery. These elastomers were known from the outset to have many desirable attributes such as high flexibility, chemical stability, and nontoxicity. However, research is now available to indicate that the high lipophilic property may cause a gradual deterioration in dynamic performance.

Silicone implants, such as finger joint prostheses in orthopedic surgery and early artificial valve balls in cardiosurgery, have been reported to collapse or suffer from other problems secondary to material deterioration. Recently, authors have also reported the deterioration and mineralization of blood pumps in artificial hearts. Such problems are not common in neurosurgery, but the degradation of a silicone CSF shunting system has been reported in one case.

Since the late 1970's, we have noticed a reduction in the elasticity of CSF shunting systems that were removed after a long period of implantation. Surface changes were observed in some of them. Because of these observations, we have examined CSF shunting systems removed from patients between 1981 and 1985, using operative microscopy, scanning electron microscopy (SEM), and energy dispersive analysis with x-rays. We also measured their ultimate tensile strength, extensibility, and 100% modulus of elasticity. On the basis of the results of these studies, we evaluated the mineralization and biodegradation of CSF shunting systems.

Materials and Methods

In this investigation, 25 CSF shunting systems which had developed various kinds of malfunction were studied. They were removed from patients in our hospitals during the study period from 1981 to 1985 (Table 1). In our hospitals, Denver CSF shunting systems were used until 1984, and Heyer-Shulte antisiphon-type double-chamber systems were implanted during 1985. One Raimondi shunting system was implanted in 1981.
### Table 1
Clinical data on 25 cases with removal of CSF shunt*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Sex &amp; Age at Removal (yrs)</th>
<th>Primary Disease</th>
<th>Cause of Shunt Removal</th>
<th>Period of Implantation (days)</th>
<th>Shunt System</th>
<th>Surface Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M, 55</td>
<td>SAH</td>
<td>wrong position</td>
<td>6</td>
<td>H-S</td>
<td>none</td>
</tr>
<tr>
<td>2</td>
<td>M, 33</td>
<td>aqueductal stenosis</td>
<td>wrong position</td>
<td>6</td>
<td>D</td>
<td>none</td>
</tr>
<tr>
<td>3</td>
<td>F, 72</td>
<td>SAH</td>
<td>wrong position</td>
<td>10</td>
<td>D</td>
<td>none</td>
</tr>
<tr>
<td>4</td>
<td>F, 71</td>
<td>chronic SDH</td>
<td>infection</td>
<td>11</td>
<td>H-S</td>
<td>none</td>
</tr>
<tr>
<td>5</td>
<td>M, 46</td>
<td>NPH</td>
<td>infection</td>
<td>14</td>
<td>H-S</td>
<td>none</td>
</tr>
<tr>
<td>6</td>
<td>M, 84</td>
<td>SAH</td>
<td>unknown malfunction</td>
<td>23</td>
<td>D</td>
<td>none</td>
</tr>
<tr>
<td>7</td>
<td>F, 70</td>
<td>SAH</td>
<td>wrong position</td>
<td>30</td>
<td>H-S</td>
<td>none</td>
</tr>
<tr>
<td>8</td>
<td>M, 67</td>
<td>NPH</td>
<td>unknown malfunction</td>
<td>33</td>
<td>H-S</td>
<td>none</td>
</tr>
<tr>
<td>9</td>
<td>F, 78</td>
<td>acoustic neuroma</td>
<td>unknown malfunction</td>
<td>35</td>
<td>H-S</td>
<td>none</td>
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<tr>
<td>10</td>
<td>M, 52</td>
<td>thalamic hemorrhage</td>
<td>peritoneal adhesion</td>
<td>51</td>
<td>H-S</td>
<td>none</td>
</tr>
<tr>
<td>11</td>
<td>M, 48</td>
<td>SAH</td>
<td>unknown malfunction</td>
<td>60</td>
<td>H-S</td>
<td>none</td>
</tr>
<tr>
<td>12</td>
<td>M, 70</td>
<td>NPH</td>
<td>peritoneal adhesion</td>
<td>65</td>
<td>D</td>
<td>none</td>
</tr>
<tr>
<td>13</td>
<td>F, 1</td>
<td>congenital hydrocephalus</td>
<td>unknown malfunction</td>
<td>80</td>
<td>H-S</td>
<td>none</td>
</tr>
<tr>
<td>14</td>
<td>M, 37</td>
<td>cerebellar hemorrhage</td>
<td>peritoneal adhesion</td>
<td>98</td>
<td>D</td>
<td>none</td>
</tr>
<tr>
<td>15</td>
<td>F, 14</td>
<td>aqueductal stenosis</td>
<td>system destruction</td>
<td>165</td>
<td>H-S</td>
<td>localized</td>
</tr>
<tr>
<td>16</td>
<td>M, 38</td>
<td>cerebellar hemorrhage</td>
<td>unknown malfunction</td>
<td>307</td>
<td>D</td>
<td>none</td>
</tr>
<tr>
<td>17</td>
<td>F, 2</td>
<td>neonatal asphyxia</td>
<td>shortening</td>
<td>350</td>
<td>D</td>
<td>none</td>
</tr>
<tr>
<td>18</td>
<td>M, 30</td>
<td>NPH</td>
<td>appendicitis</td>
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<td>D</td>
<td>dull</td>
</tr>
<tr>
<td>19</td>
<td>M, 2</td>
<td>neonatal ICH</td>
<td>unknown malfunction</td>
<td>740</td>
<td>D</td>
<td>localized</td>
</tr>
<tr>
<td>20</td>
<td>M, 75</td>
<td>cerebellar hemorrhage</td>
<td>intestinal penetration</td>
<td>1360</td>
<td>D</td>
<td>none</td>
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<tr>
<td>21</td>
<td>F, 41</td>
<td>SAH</td>
<td>subcutaneous reaction to silicone, traction pain</td>
<td>1711</td>
<td>D</td>
<td>diffuse</td>
</tr>
<tr>
<td>22</td>
<td>M, 57</td>
<td>SAH</td>
<td>unknown malfunction</td>
<td>1750</td>
<td>D</td>
<td>none</td>
</tr>
<tr>
<td>23</td>
<td>M, 4</td>
<td>subdural empyema</td>
<td>shortening</td>
<td>1752</td>
<td>R</td>
<td>none</td>
</tr>
<tr>
<td>24</td>
<td>M, 20</td>
<td>fibrous dysplasia</td>
<td>septic meningitis</td>
<td>2230</td>
<td>D</td>
<td>localized</td>
</tr>
<tr>
<td>25</td>
<td>F, 23</td>
<td>thalamic tumor</td>
<td>system destruction</td>
<td>3533</td>
<td>D</td>
<td>diffuse</td>
</tr>
</tbody>
</table>

*Abbreviations: CSF = cerebrospinal fluid; SAH = subarachnoid hemorrhage; NPH = normal-pressure hydrocephalus; SDH = subdural hematoma; ICH = intracerebral hemorrhage; D = Denver system; H-S = Heyer-Shulte system; R = Raimondi system.

### Examination of Shunt Material

All 25 shunting systems were examined under an operative microscope at ×10 magnification. The removed materials were closely observed around the circumferences of their entire length.

The surface and cross-sectional condition of eight Denver and one Heyer-Shulte CSF shunting systems were examined by SEM. The materials that showed surface changes under an operative microscope were tested for atomic quantity and relative mass of surface deposits using energy dispersive analysis with x-rays.

The materials studied by these techniques included the following: Sample A: New tubing within 6 months of being manufactured; Sample B: Tubing kept in vitro at ordinary temperatures for six years; Sample C: The tubing from Case 17 after 1 year of implantation; Sample D: The tubing from Case 19, which, after 2 years of implantation, had localized surface changes; Sample E: The tubing from Case 20 after 3 years of implantation; Sample F: The tubing from Case 21, which, after 5 years of implantation, had diffuse surface changes; Sample G: The tubing from Case 24, which, after 6 years of implantation, had localized surface changes; Sample H: The tubing from Case 25, which, after 10 years of implantation, had diffuse surface changes; Sample I: The tubing from Case 15, which, after 165 days of implantation, had surface changes on the folding portion; and Sample J: The tubing from Case 20 (as in Sample E), subjected to a deposit-removal treatment by immersion in ethylenediaminetetra-acetic acid.

### Measurement of Physical Properties

Stress-strain curves were obtained using an elastometric tester for the samples listed in Table 2. The ultimate tensile strength, extensibility, and 100% modulus were obtained from these curves. Since this testing required a certain size and shape of the specimens, the tubes of three specimens which were 20 mm long were examined. These specimens were sampled from the abdominal portion of the shunts. The tests were carried out at a cross-head speed of 10 cm/min with a gauge length set at 10 mm, giving a strain rate of 1000% per minute.

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* Scanning electron microscope, Model S-510, manufactured by Hitachi Ltd., Tokyo, Japan.
† Energy dispersive analyzer, Model EMAX-1770, manufactured by Horiba Co., Kyoto, Japan.
‡ Elastometric tester, Model DCS-2000, manufactured by Shimazu Co., Kyoto, Japan.
Results

Operative Microscopy Studies

Coarse white deposits were seen on the surfaces of four Denver systems, two of which were found to have undergone such surface changes over almost their entire length, beginning just below the device and ending just above the intraperitoneal insertion. One of these was very fragile, and the other was difficult to remove from the patient because of its tight adhesion. In the remaining two cases that underwent localized surface changes, there were surface deposits on the tubing 5 to 7 cm from the shunting device (Fig. 1) and also scattered sporadically over a segment 2 to 8 cm from the device. In all of these four cases, surface changes were greatest in the region about 6 cm from the device. This region is located quite close to the nuchal line. In the two cases that showed diffuse changes, the substance in the nuchal region showed a crystalline structure.

Other surface changes were also observed. In one case, loss of surface luster was observed over a 10-cm length of tube at the abdominal wall. In another case, the surface irregularity was on the inside of a tube fold in the abdominal portion.

SEM Study of Tube Surface

The surface of Sample A showed gyri-like wrinkles (Fig. 2 left). Microscopic holes between about 0.3 and 0.5 μm in size were seen on the surface and on the cross-sectional surfaces. Tiny particles of a substance less than 0.5 μm in size were present in the material (Fig. 3 left). In Sample B the surface wrinkles were slightly reduced but no other changes were observed, and in Sample C the surface was nearly smooth and the microscopic holes were about 1 μm in size. The surface of Sample D was rough and showed a white substance (Fig. 4 left). The thickness of the material was reduced to 430 μm (28% loss). The microscopic holes were approximately 1 μm in size. The tiny particles were more than 1 μm in size and showed a crystalline appearance (Fig. 3 right). In Sample E the wrinkles on the surface had almost disappeared (Fig. 2 right), and the tiny particles were between 3 and 4 μm in size. The surface of Sample F was destroyed by cracking and was covered with a thick substance (Fig. 4 right), with numerous crystalline particles appearing on the surface of the substance (Fig. 5 left). The thickness of the original material was reduced to 330 μm (45% loss).

In Sample G the wrinkles on the tube surface were preserved but small plaque changes were seen. The surface changes in Sample H were similar to those in Sample G. The maximum diameter of the microscopic holes was about 10 μm, and most of the tiny particles were between 5 and 10 μm in size. The material was reduced in thickness to 360 μm (40% loss) (Fig. 6). Sample I showed nodular protrusions and wide cracks at a site where the tube was folded (Fig. 7). The surface of Sample J showed destructive erosion (Fig. 5 right).

Energy Dispersion Analysis of Surface Substances

Energy dispersion analysis using x-rays revealed a large silicon peak and a minimal barium peak in the
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**FIG. 3.** High-magnification scanning electron micrographs showing tiny particles in the material. *Left:* Tiny particles, 0.1 to 0.5 μm in size, are seen in the new material. *Right:* Sample D. The particles have increased in size (asterisk) and show a crystalline appearance.

**FIG. 4.** High-magnification scanning electron micrographs showing localized and diffuse surface changes in the material. *Bar = 1 mm.* *Left:* Surface deposit formed by plaque in Sample D (from Case 19). *Right:* The surface in Sample F (from Case 21) has a craggy appearance. Note the reduction in thickness of the right upper portion.

**FIG. 5.** High-magnification scanning electron micrographs showing the crystalline small granules of the surface deposit in Sample F (*left*) and surface erosion in the same material after treatment with ethylenediaminetetra-acetic acid solution (*right*).
FIG. 6. Scanning electron micrograph showing a cross section of the surface of Sample H (from Case 25). Microscopic holes (arrows) 10 μm in size are seen, and the irregularity of the outer-edge surface indicates deterioration of the original material.

<table>
<thead>
<tr>
<th>Sample†</th>
<th>Ultimate Tensile Strength (kg/sq cm)</th>
<th>Extensibility (%)</th>
<th>100% Modulus (kg/sq cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>54.2 ± 3.0</td>
<td>1077 ± 36</td>
<td>8.4 ± 0.2</td>
</tr>
<tr>
<td>B</td>
<td>61.1 ± 5.0</td>
<td>728 ± 77</td>
<td>9.4 ± 0.5</td>
</tr>
<tr>
<td>C</td>
<td>57.4 ± 2.7</td>
<td>459 ± 42</td>
<td>20.5 ± 0.3</td>
</tr>
<tr>
<td>D</td>
<td>56.9 ± 3.5</td>
<td>425 ± 68</td>
<td>17.8 ± 0.3</td>
</tr>
<tr>
<td>E</td>
<td>53.1 ± 6.6</td>
<td>502 ± 90</td>
<td>13.8 ± 1.3</td>
</tr>
<tr>
<td>F</td>
<td>34.4 ± 2.3</td>
<td>238 ± 25</td>
<td>17.2 ± 3.4</td>
</tr>
<tr>
<td>G</td>
<td>29.8 ± 1.2</td>
<td>228 ± 54</td>
<td>-</td>
</tr>
</tbody>
</table>

* Values are expressed as the mean ± standard deviation. CSF = cerebrospinal fluid.
† For details of samples see text.

TABLE 3
Possible factors contributing to calcification on artificial blood pumps*

- animal species
- age of host
- hormone level
- type of material (natural or synthetic)
- local hemodynamics
- shear stress
- surface defects and abnormalities
- anticoagulation regimen
- local thermal effects
- role of lipids and lipoproteins
- local surface charge effects
- absorbed proteins
- hydrophobicity of material
- thrombus

* These factors were discussed during the World Symposium on Artificial Hearts in 1979, and have been described by Coleman.6

Reduction of the Physical Properties

The ultimate tensile strength varied from 61.0 kg/sq cm in unused material to 29.8 kg/sq cm in material that had been implanted for 6 years. In this test, all specimens broke away at the edge of the chuck. Specimens in that condition had a lower tensile strength compared with that given in previous reports.36,37 The extensibility of the materials varied from 1077% in new material to 228% in a material that had been implanted for 6 years. Although the time dependency of the increase in the 100% modulus of elasticity could not be clarified in this test, the difference between the value in an unused shunting system and that in implanted materials was clearly observed.

Discussion

In 1945, Dow Corning Corporation began industrial-scale production of Grignard-process silicone based on Kipping’s principle.22 The good resistance of silicone to heat made it a potentially superior medical material since its physical properties would not be affected by thermal sterilization. In addition, its high flexibility and biocompatibility make silicone well suited for in vivo implantation use.6,37 A silicone rubber for medical use, Silastic, was marketed in the early 1950’s.3 Ever since, silicone rubber as an in vivo implant material has been used increasingly in many fields of surgery. In neurosurgery, silicone rubber was introduced in the late 1950’s into CSF shunting systems designed for the treatment of hydrocephalus.4,29 During the 30 years since then, it has been the only material used for CSF shunting systems. Many types of shunting devices are now available.28

Polymers undergo biodegradation in a biological environment. Their modalities of change, however, are type-dependent.33 According to Kronenthal,19 polymers biodegrade via the following four processes: 1) their higher-order structures are destroyed by hydration; 2) covalent bonds of the polymer main chain are split; 3) as covalent bond cleavage proceeds, the molecular weights of the polymers are reduced; and 4) material fragments are solubilized, digested by macrophages, and completely absorbed.

It has been said that biodegradation-resistant polyethylene terephthalate requires a mean time of 10 ± 2 years for a 50% reduction in its strength and 30 ± 7 years for complete degradation when left to undergo the process of biodegradation.31 In a long-term experi-
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![Image of electron micrographs showing structural changes at the site of a fold in Sample 1 (from Case 15). There are bumps, deep cracks, and holes in the surface at the fold. The flat surfaces on both sides were brought in contact by folding.](image1.png)

**FIG. 7.** High-magnification scanning electron micrographs, oblique view (left) and view from above (right), showing the structural change at the site of a fold in Sample 1 (from Case 15). There are bumps, deep cracks, and holes in the surface at the fold. The flat surfaces on both sides were brought in contact by folding.

![Image of energy dispersive analysis using X-rays showing the elements detected on the surface of new material.](image2.png)

**FIG. 8.** Energy dispersive analysis using X-rays. **Left:** Only silicon (Si) and barium (Ba) are detected from the surface of new material. Gold (Au) is used for vapor-coating in scanning electron microscopy. **Center:** Calcium (Ca) and phosphorus (P) are evident in the surface deposit. **Right:** Pure aluminum (Al) is detected from the tiny particles, as shown in Fig. 3 left.

Van Noort, *et al.*, reported that subcutaneous implantation of silicone rubber in guinea pigs resulted in its degeneration, probably as a result of the absorption of a calcific surface deposit. They hypothesized that the reduction in properties was caused not by molecular changes in the silicone rubber or by the absorption of lipid, but by surface damage. Possible causes of surface mineralization were discussed during the World Symposium on Artificial Hearts held in 1979 (Table 3). The following problems related to the material have been reported in other fields of surgery: fractures of finger joint prostheses, lymphadenopathy or synovitis due to the breaking apart of silicone particles, migration of ball-valve prostheses due to reduction in size, and artificial blood-pump problems owing to mineralization occurring on the diaphragm.

Although various system problems and reactions affecting silicone rubber in CSF shunting systems have been well documented, reports on material-related prob-
Problems are uncommon in neurosurgery. The present study of a series of CSF shunting systems removed over 5 years has demonstrated a high incidence of surface changes and a reduction of the physical properties of these materials. Characteristic changes observed by SEM analyses were wrinkles on the surfaces, microscopic holes, and tiny aluminum particles, as well as a general deterioration of the materials. Distinct gyri-like wrinkle formations were observed on the surface of new material. In this new material, the microscopic holes and tiny particles were less than 0.5 μm in diameter. The wrinkles tended to disappear in materials that had been implanted for a long time. The microscopic holes gradually increased in size, reaching 1 μm 1 year after implantation and as large as 10 μm after 10 years. The tiny particles of aluminum also increased in size (to 1 μm at 1 year after implantation, 3 to 4 μm after 4 years, and 10 μm after 10 years). This growth probably coincided with the reduction in physical properties. The maximum content of aluminum in Silastic MDX-4-4515, a widely used silicone rubber for CSF shunting systems, is 100 ppm in manufacturing. The role and the alteration of the form of the aluminum particles in biodegradation have not been investigated or reported in the past. These particles contained silicone if the material had been implanted for a long time. This may indicate that the particles either absorbed silicone molecules or were altered to a silicone compound. We suppose that these changes in the microscopic holes and aluminum particles may be a consequence of the degradation of the silicone rubber.

We have determined that the process of surface mineralization in silicone rubber CSF shunting systems involves the deposit of calcium phosphate. With regard to the influence of the age of the host on the mineralization process, there is currently no generally accepted theory. We performed discriminant analyses of nine Denver systems that had been implanted for more than 300 days. The systems were divided into a mineralized and a nonmineralized group. The variables used were the age of the host at implantation (years) and the duration of implantation (days). The results of the discriminant analysis were expressed as F-value (2,6): 4.313; and Mahalanobis D-square: 4.529. These two variables correlated with the incidence of mineralization (p < 0.1). Mineralization tended to occur more frequently among younger patients in whom a system had been implanted for a long period.

The nonlustrous surface changes showed no structural alterations in preliminary SEM analyses. The flaws in the folding portion were wide cracks and microscopic holes 20 μm in diameter. The cause of these changes is considered to be compressive strain due to folding of the material. No calcium phosphate was detected on the folding portion in our material. This finding may be due to the short interval of implantation.

In the present study, the most frequent and serious mineralization occurred in regions near the nuchal line. Characteristically, the shunt tube at this location runs from the subgaleal layer to the subcutaneous layer. In other words, the tube penetrates the galea or occipital venter of the occipitofrontal muscle at a site near the nuchal line. As a consequence, a tube at this site is under mild constricive stress and may become fixed more easily than at other locations. Furthermore, the shunt system is implanted while the patient's neck is in a position of opposite rotation. The length of the system's path is minimal in this position and it is maximized by ipsilateral neck rotation. Rotation of the neck exerts a repeated tensile strain on the system. Thus, mechanical stress is very likely to be the most important factor in the mineralization of CSF shunting systems.

Deterioration of the silicone structure was suggested in the mineralized portion. The thickness of the materials decreased by about 30% with localized mineralization and by more than 40% with diffuse mineralization. This indicates that silicone molecules dissolved from the surface and suggests the existence of a fourth stage of degradation described by Kronenthal. The dissolving of silicone molecules seems to be influenced by the mineralization of the surface. This finding agrees with the results of the experiment by van Noort.

The reduction of physical properties causes degradation in polymers. The ultimate tensile strength and extensibility in our specimens gradually decreased in the first 3 years after implantation and became remarkably altered after 5 years. These results suggest that the CSF shunting system became progressively less elastic and more fragile with time.

Conclusions

It has been shown that mineralization and biodegradation occur in CSF shunting systems as in other prostheses. In certain cases these substantial alterations become remarkably advanced after 5 years of implantation. Also, these alterations are hypothesized to proceed through a galeal penetration of the systems. Exactly what forms these alterations take has not as yet been established; however, further investigation is expected to solve these problems. At present, however, periodic examination should be undertaken in cases where CSF shunting systems have been implanted for more than 5 years, particularly in younger patients.

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References


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