

## A synthetic dural prosthesis constructed from hydroxyethylmethacrylate hydrogels

SANJIV BHATIA, M.CH., PETER R. BERGETHON, M.D., SUSAN BLEASE, B.D.S., THOMAS KEMPER, M.D., ARTHUR ROSIELLO, M.D., GUY P. ZIMBARDI, M.A., CARL FRANZBLAU, PH.D., AND EDWARD L. SPATZ, M.D.

*Departments of Neurosurgery and Biochemistry, Boston University School of Medicine, and Neurological Unit, Boston City Hospital, Boston, Massachusetts*

✓ Hydroxyethylmethacrylate (HEMA) hydrogels were investigated for their suitability as a dural prosthesis. Poly-HEMA has many characteristics required for an artificial dural substitute: it is durable, flexible, easily prepared, inexpensive, easily sterilized and handled, easily shaped, and known to be chemically inert and nontoxic. Sheets made of plain HEMA were evaluated as dural substitutes in rats and rabbits after either craniotomy or laminectomy with dural resection. Histological evaluations of the prostheses and the underlying tissues were undertaken at various time points from 2 to 9 weeks postoperatively. There was minimal tissue response to the implanted HEMA gel in contrast to marked thickening of the overlying leptomeninges and cortical herniation in the control animals. It is concluded that HEMA gels fulfill the essential criteria for an effective dural substitute.

**KEY WORDS** • polymer • hydrogel • hydroxyethylmethacrylate • dural substitute • rat • rabbit

IT is usually the aim to provide a complete dural closure after an intracranial or intraspinal operative procedure; however, this is not always possible. Repair of the dura mater following traumatic, neoplastic, or inflammatory destruction, surgical excision, or congenital absence is considered the indication for duraplasty. Dural fistulas that result without successful duraplasty predispose a patient to cerebrospinal fluid (CSF) leakage, meningitis, abscesses, and the formation of meningocerebral cicatrix with subsequent risk of focal epilepsy.<sup>10,29</sup> The choice of an appropriate material for replacement of the dura has posed a problem for the greater part of this century.

This study investigates the biocompatibility of hydroxyethylmethacrylate (HEMA) hydrogel *in vivo* and its use as a dural prosthesis. This hydrogel has been shown to be nontoxic and durable and has been used in cell culture systems and contact lenses.<sup>7,11,31</sup> Hydrogels made from poly-HEMA are inexpensive, available in many sizes, easily sterilized, and flexible, and they have a smooth surface.

### Materials and Methods

#### *Manufacture of Hydrogels*

Plain HEMA hydrogels are made by preparing a 1:1:1 (vol/vol (20 ml each)) mixture of ethylene glycol, 2-HEMA monomer, and

an aqueous buffer (0.05 M Tris-HCl, 0.15 M NaCl, pH 7.4). Collagen-HEMA hydrogels are prepared in similar fashion except that the aqueous buffer also contains solubilized rat-tail collagen at a concentration of 1 mg/ml, as described previously.<sup>7</sup> This preparation is degassed under low pressure and, while on ice, 2 ml of 12% sodium bisulfite and 2 ml 6% ammonium persulfate solution are added. Flat sheets of hydrogel are prepared by polymerization after injection of the monomer-catalyst mixture into a form made from a sandwich of two precleaned glass microscope slides spaced by a pair of No. 1 coverslips. The slides are incubated at 37°C for 2 hours, at which time polymerization is complete. The sheets of HEMA are then exhaustively dialyzed in a buffer solution (0.05 M Tris-HCl, 0.15 M NaCl, pH 7.4). The polymer sheets are protected during dialysis by placement in a plastic cage that ensures free flow of dialysate while protecting the gel material. At the completion of dialysis, the gels are crystal clear and are stored in buffer solution (0.05 M Tris-HCl, 0.15 M NaCl) at 4°C until needed. When needed for a duraplasty, the HEMA gel is cut to the appropriate size and sterilized by immersion in 10% penicillin-streptomycin and exposure to ultraviolet germicidal irradiation for 2 hours. Sterilized gels are stored in sterile Puck's saline (free of Ca<sup>++</sup> and Mg<sup>++</sup>) at 4°C until used in surgery.

#### *Duraplasty*

Duraplasty was performed on outbred rats (CrI:CD BR COBS; Charles River Laboratories, Wilmington, MA) ranging in weight from 300 to 450 g and on New Zealand White rabbits (Pine Acres Rabbitry, West Brattleboro, VT) weighing 1.5 to 2.0 kg. Rapid onset of anesthesia and muscle relaxation were achieved with intramuscular ketamine, 80 mg/kg for rats and 35 mg/kg for rabbits, and

xylazine, 14 mg/kg for rats and 5 mg/kg for rabbits. Supplemental doses of anesthesia were given as necessary.

In the rat experiments, groups of four animals each had artificial duras placed intracranially, were sham-operated controls, or were unoperated controls. After the cranium was shaved and prepared, a midline incision was made over the scalp and the periosteum was stripped and retracted. The parietal bone was thinned with a Dremel drill fitted with an oblong cutting burr. The dura was stripped from the inner table with a nerve hook inserted through a small opening in the bone. A 10 × 5-mm craniotomy was completed with an angled 1-mm Kerrison rongeur. The transparent dura was opened with a skin hook and nerve hook. A small piece of HEMA gel shaped to fit the craniotomy was placed over the exposed cortex with the edges of the gel placed beneath the margins of the opened dura. In the sham-operated animals, no HEMA synthetic dura was placed, and the skull defect was not closed with any cranioplasty material. The scalp was closed with three or four interrupted silk sutures.

In the rabbit experiments, all animals had a 1.0- to 1.5-cm craniectomy in the left parietal region made with the electric drill and a small upcutting rongeur. Of these, 37 animals also underwent dorsal laminectomy over three to four vertebral segments performed with a drill and a small Leksell rongeur. All procedures were performed using microsurgical technique. Five subgroups of animals were studied after sacrifice at 6 or 9 weeks postsurgery: 1) craniectomy and laminectomy—control (nine rabbits); 2) craniectomy and laminectomy with duresctomy—control (12 rabbits); 3) craniectomy, laminectomy, and duresctomy with plain HEMA duraplasty (six rabbits); 4) craniectomy, laminectomy, and duresctomy with collagen-HEMA duraplasty (four rabbits); and 5) craniectomy, laminectomy, and duresctomy with HEMA and collagen-HEMA sandwich duraplasty (six rabbits). All grafts were overlaid on the dura covering the dural defect. A small piece of muscle was placed over the gel in the spinal operations to keep the graft in place.

#### *Histological Study*

Between 14 to 63 days postoperatively, animals were sacrificed following induction of intraperitoneal sodium pentobarbital anesthesia. The rats were perfused through the left ventricle with 200 ml of normal saline followed by 300 ml of 10% buffered formalin and then decapitated. Excess tissue was removed and the head was immersed in 10% buffered formalin for 4 days and placed in 10% ethylenediaminetetraacetic acid until decalcification was complete. The rabbits were sacrificed after an intravenous injection of 100 mg sodium thiopental. Specimens from the rabbits were obtained following reexposure of the operative areas. A segment of the spinal column that included the operative area was excised. A circumferential craniectomy was made 0.5 cm outside the area of the initial cranial operation and a conical piece of brain along with the overlying cranium was removed. Both of these pieces were immersed in 20% formaldehyde for fixation followed by decalcification. The nervous tissues, adjoining structures, and gel were embedded in paraffin and cut into coronal sections 6 μm thick. The tissue sections were stained with hematoxylin and eosin and trichrome blue.

### **Results**

We have found that HEMA hydrogels are easily prepared and can be stored in a sterile condition for over a year without any change in clarity, flexibility, or sterility. The hydrated hydrogel material can be cut with scissors to the desired shape and can be handled and manipulated with ease.

All of the operated rats recovered from the surgery without complication. The general health and behavior of each group of animals was comparable, including the unoperated and sham-operated controls and the duraplasty animals. No animal showed signs of intracranial infection, focal paresis, or evidence of seizures.

Initially, a high rate of paraparesis was noted immedi-

ately following laminectomy in the rabbits (four of these five animals were sacrificed). Although this morbidity rate was rapidly reduced as experience was gained with the procedure, all subsequent experimental animals were administered 2 mg of dexamethasone intramuscularly the day prior to surgery. Of the subsequent 24 animals, two animals were sacrificed, one after developing paraparesis (duresctomy-only group) and one that chewed its feet and was sacrificed at 3 weeks (collagen-HEMA gel group). One animal developed wound dehiscence that required secondary suturing. No animal developed a CSF leak from either the cranial or spinal wound.

One rat duraplasty site was reopened under anesthesia at 56 days. The HEMA hydrogel was observed to be lying flat, was not adherent to any tissue, and had remained clear. Elevation of the hydrogel from under the dural edges resulted in an outpouring of clear fluid under apparent pressure, thus indicating that a watertight seal had been achieved without sutures. The hydrogel was easily removed from the duraplasty site without adherence to the underlying tissues. Macroscopic inspection of the hydrogels after fixation and decalcification showed that they remained clear and flexible.

#### *Histopathological Findings*

*Rat Series.* In the rat experiments, histological examination of the HEMA duraplasties and the underlying cortical tissues showed a band of connective tissue at the edges of the graft extending from the leptomeninges to the overlying surgical defect. A variable degree of destruction of the cortical and surrounding tissues was found in the operated animals. This microscopically variable damage was attributed to injury during surgery, because the cases in which bleeding occurred during surgery could be correlated with the most severe damage seen on the microscopic sections. Where mild injury had occurred, the overlying meninges were slightly thickened, there was a slight increase in connective tissue at the edges of the graft, minimal thinning of cortical layer I, a mild increase in glial cells, and minimal distortion of neurons in layer II. In cases of severe cortical destruction, there was no change in orientation of neurons but a marked increase in connective tissue at the edges of the graft and complete or partial loss of layer I were noted.

All of the sham-operated rats showed mild-to-severe cortical herniation through the dural defect. There was a marked increase in connective tissue and some thickening of the leptomeninges in all animals. Two animals showed a variable increase in the number of glial cells in layer I and some flattening of neurons. One animal showed minimal changes in the underlying cerebral cortex, and another animal exhibited neuronal loss of layer I and layer II, and some cellular loss extending into layer III.

Compared to the neurohistology of the unoperated controls, both the sham-operated and the duraplasty rats showed changes consistent with physical damage to the cortex and overlying tissues only. There was no evidence of toxic damage or inflammatory changes in the cerebral tissues attributable to the HEMA implants.

*Rabbit Series.* Results of the experiments in rabbits are shown in Fig. 1 (craniectomies) and Fig. 2 (laminectomy).

## Synthetic dural substitute from HEMA hydrogels

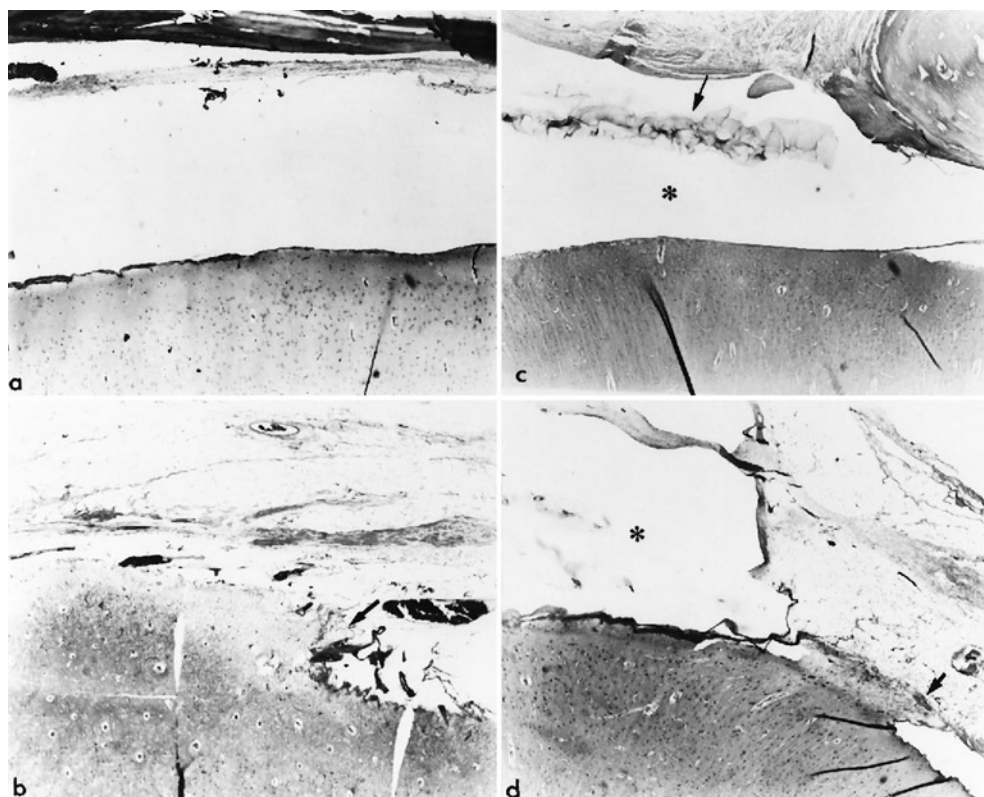


FIG. 1. Photomicrographs showing results of hydroxyethylmethacrylate (HEMA) hydrogel experiments in the rabbit brain. a: Section of cortex in a control animal without durectomy. b: Section of cortex in a control animal after durectomy showing disruption of the normal architecture, adhesions, and overlying scar formation at the site of cortical hemi-atom. c: Section showing preservation of the normal cortical architecture under the plain HEMA hydrogel at the durectomy site. d: Section showing preservation of the normal architecture under the plain HEMA hydrogel adjacent to a meningocerebral cicatrix which formed at a site unprotected by the hydrogel. H & E.

tomies). There were nine control animals, all of which underwent localized craniectomies and dorsal laminectomies. Histological examination of the spinal cord specimens showed a thicker dorsal dura in comparison to the ventral dura. The dorsal dura in the region of the laminectomies was not adherent to the cord in any specimen. Two animals showed evidence of spinal cord injury in the posterior column but no adhesions were seen in the overlying dura. In the craniectomy-only animals, no adhesions were noted between the brain and the intact dura.

Twelve animals underwent durectomy (both brain and cord) alone and five died or were sacrificed because of surgical complications as described above. The remaining seven animals all showed dense scar formation at the site of the durectomy with loss of the subarachnoid space. Adhesions to the spinal cord and to the brain were present in all animals. There was a variable degree of herniation of the brain and spinal cord. Cortical layer I showed a variable degree of thinning associated with an increase in glial cells. There was no appreciable change in the neurons in layer II. These changes were attributed to the physical distortion of the tissues following herniation and not at surgery.

Sixteen animals underwent HEMA gel duraplasty, six with plain HEMA, four with collagen-HEMA, and six with a sandwich gel in which the inner layer (contacting

the neural structures) was plain HEMA and the outer layer was collagen-HEMA. The duraplasty sites in the six animals with the plain HEMA gel showed minimal or no fibrotic reaction at the site of the durectomy under the gel. Fibrotic reactions were noted to be limited to the edges of the graft where it had lifted off the dural surface. This edge effect contrasted with the lack of significant fibrotic changes in the subarachnoid subdural space in the central area under the plain HEMA gel. The cellular and architectural integrity of the neural structures in the brain and spinal cord showed no abnormal reaction except as attributable to superficial cord contusion from surgery, in spite of the significant compression of the spinal cord exerted by the addition of two layers of HEMA hydrogel to the already restricted space of the normal rabbit spinal canal.

None of the four animals that underwent duraplasty with collagen-HEMA gel sustained intraoperative neural injury, although one animal was sacrificed at 3 weeks because of self-mutilation. All of these duraplasties showed dense fibrosis and adhesions at the interface between the gel and the spinal cord and brain. These adhesions were noted throughout the region of contact between the collagen-HEMA gel and were not an edge-effect as seen in the plain HEMA gel duraplasties (Fig. 2).

The six animals that underwent duraplasty with the sandwich gel did well clinically and no significant fibro-

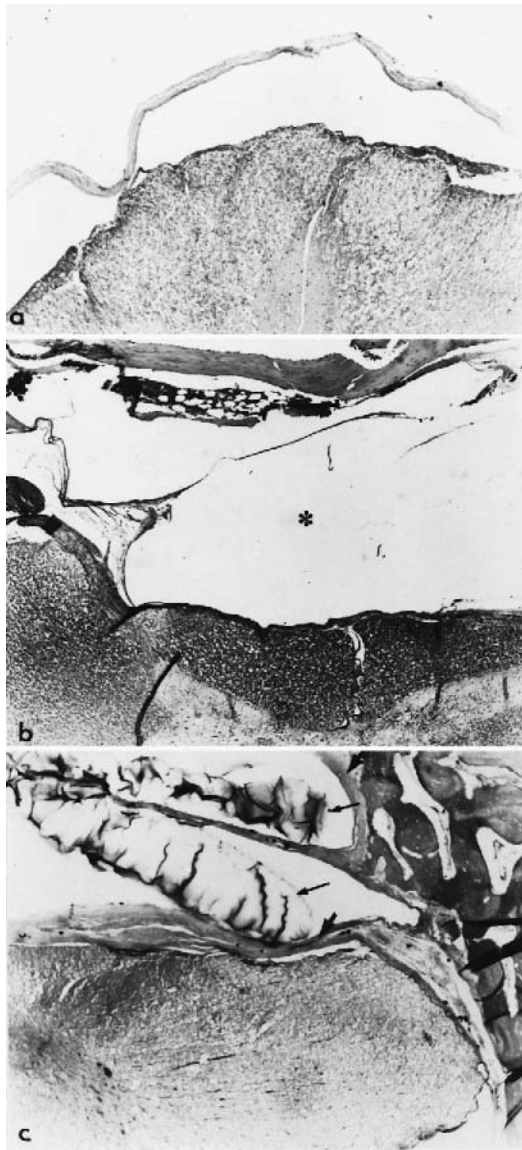


FIG. 2. Photomicrographs showing results of hydroxyethyl-methacrylate (HEMA) hydrogel experiments in the rabbit spinal cord. a: Transverse section of the spinal cord in a control animal without durotomy. b: Section showing preservation of normal spinal cord architecture under the plain HEMA hydrogel at the site of laminectomy with durotomy. c: Section showing exuberant scar formation elicited by the presence of the collagen-impregnated hydrogel. H & E.

sis was noted between the plain HEMA gel and the underlying neural structures. The collagen-HEMA surface that faced away from the neural structures was noted to have dense fibrotic reaction at its tissue interface with the extradural structures (Fig. 2c).

### Discussion

Disruption of the continuity of the dura, in which the underlying arachnoid, pia, or cortex is uninjured, results in

regeneration of the dura without formation of meningo-cerebral cicatrix.<sup>20,29,30,34</sup> A meningo-cerebral cicatrix forms after injury to the pia-arachnoid,<sup>14,29,30</sup> which is the predisposing factor causing connective tissue invasion from the dura, thus resulting in meningo-cerebral adhesions. The formation of adhesions is an important element in the production of posttraumatic or postoperative complications such as epilepsy.

A consensus exists that the material to be used for duraplasty should simulate the properties of the dura mater.<sup>16,19,23,26,32,33,35,38,39,42</sup> Ideally, the substitute would be nontoxic, nonabsorbable, biologically inert, resistant to disintegration, and protective without producing a glial reaction or meningo-cerebral adhesions. Furthermore, the material should be easily sterilized and manipulated, readily available, and economical. A wide range of duraplasty materials have been investigated in the last century (Appendix A). The experience with these materials is summarized in Appendix B.

To fully address the formation of meningo-cerebral adhesions, the interactions of cells with their extracellular substrate should be considered. A previous study has shown that gels made of poly-HEMA do not support cell spreading.<sup>7</sup> On the other hand, the addition of collagen to the hydrogel material provides a substrate conducive to cell adherence, proliferation, and growth. These modified hydrogels would be expected to elicit a local invasion of fibroblasts and other mesenchymal cells and to support both protein adhesion and the accumulation of extracellular matrix at the cell-hydrogel interface. In this study, these poly-HEMA hydrogels have been evaluated as a dural substitute. Because HEMA hydrogels are hydrophilic they absorb water, which accounts for 30% to 40% of the final volume of the matrix. These gels are not very cohesive but are adhesive. The material could be easily handled and cut into any shape, and the remainder reused; however, it could not be sutured. On contact with the dry dural or cortical surface it formed a good seal although it could be lifted off with forceps again if repositioning were required. On reopening the wound 6 to 9 weeks later, there was no evidence of CSF leak or local pooling of CSF. These adhesive qualities may make suturing unnecessary in many cases; however, development of a biological adhesive to be used with these materials is now being undertaken in our laboratories.

Histological evaluation of the brain and spinal cord in the region of the durotomy showed that in the absence of a gel the brain and spinal cord tended to adhere to the overlying scar. This is clearly reminiscent of the changes seen in patients undergoing reoperation when there has been incomplete dural closure at the time of initial surgery. In contrast, none of the animals with a plain HEMA hydrogel showed any change in the superficial layers of the brain or spinal cord. It is also remarkable that, in spite of the chronic compression secondary to the two layers of gel, the spinal cord did not show any histological change. With the interposition of the plain HEMA gel this scar can be minimized. This work has shown that duraplasty using plain HEMA hydrogel prevents formation of these adhesions.

In many cases when a dural substitute would be required, damage to the underlying cortex would be expect-

# Synthetic dural substitute from HEMA hydrogels

ed. In the rat experiments, the underlying cortex was damaged in both sham-operated and duraplasty animals. Review of these cases showed that, although tissue damage does occur due to the physical trauma, the presence of the HEMA graft does not exacerbate the damage and may in fact attenuate the associated pathological changes. At the edges of the grafts in these cases, the increased connective tissue accumulation is probably a similar process to that described above in rabbit experiments and shown in Fig. 1d. It seems reasonable to postulate that HEMA hydrogel significantly attenuates the cellular proliferation and connective tissue accumulation leading to fibrosis where it is in contact with the cortical tissue but that, at the edges where the gel ends, the more natural course of fibrotic change occurs. This raises the question of whether this edge-effect fibrosis could be minimized by extending coverage of the HEMA duraplasty significantly beyond the local region at the site of an injury or duraplasty.

As expected, collagen-impregnated gel induces a profound fibrotic reaction on the neural surface thus making this composition unsuitable for use adjacent to the brain or spinal cord; however, when used in a heterogeneous composition with collagen gel as the outer layer, its ability to provoke a fibrotic reaction can help to seal off the area, while a plain HEMA inner layer protects the neural structures from adhesion. Plain HEMA gels have the ability to be lifted easily from the neural surface, which can be of substantial benefit in a patient requiring reexploration of a previously operated area.

Because the plain HEMA hydrogels do not support cell adherence or proliferation, it would be expected that fibrosis or neomembrane formation would be no more likely to occur in the long term than it was over the 2-month period of these experiments. Longer-term experiments in which gels remain *in situ* for 6 to 18 months are planned so that neomembrane formation by other biological mechanisms can be excluded. The experience reported here indicates that the use of poly-HEMA-based hydrogels may well approach the ideal dural substitute.

## Investment Disclosure

The authors have no financial interest or investment in the materials described in this paper.

## Appendix A

### Materials Used as Dural Substitutes

#### Metals

Aluminum foil;<sup>10</sup> gold foil;<sup>6</sup> nickel plate;<sup>10</sup> platinum foil;<sup>25</sup> silver foil;<sup>10</sup> stainless-steel plate;<sup>10</sup> tantalum.<sup>30</sup>

#### Viable Animal Membranes

Autologous grafts: fat,<sup>10,29</sup> fascia lata,<sup>39,41</sup> pericranium,<sup>39,41</sup> temporalis fascia.<sup>18,39,41</sup>

#### Nonviable Animal Membranes

Allantoic membrane;<sup>10,30</sup> amnioplastin (human amniotic membrane);<sup>10,30</sup> Cargile membrane (prepared ox peritoneum);<sup>10,30</sup> cat gut;<sup>10</sup> collagen;<sup>17,18,21</sup> dura (lyophilized human cadaver);<sup>1,15,22,23,32,35</sup> fibrin: film;<sup>4</sup> adhesive sealant;<sup>9</sup> Gelfoam (gelatin film).<sup>8</sup>

#### Miscellaneous Membranes

Cellophane;<sup>10</sup> celluloid or celloidin;<sup>30</sup> isobutyl 2-cyanoacrylate;<sup>40</sup> L.R. Resin (polysiloxane-carbonate copolymer);<sup>33</sup> Marlex (polypropylene mesh);<sup>12</sup> mica;<sup>10</sup> nylon;<sup>16</sup> Orlon;<sup>16</sup> polyethylene;<sup>18</sup> polyvinyl alcohol film;<sup>30</sup> polyvinyl sponge;<sup>13</sup> rubber;<sup>25</sup> Silastic (silicone-coated dacron);<sup>5,21</sup> Tecoflex (polyurethane);<sup>33</sup> Teflon cloth;<sup>38</sup> Teflon cloth coated with methyl 2-cyanoacrylate adhesive;<sup>3</sup> Vicryl (polygalactin 910) mesh;<sup>24</sup> Vinyon-N.<sup>37</sup>

## Appendix B

### Tissue Reactions Associated With Material Used for Duraplasty

Inflammatory response, encapsulating neomembrane, meningocerebral adhesions, and resorption are associated with: alkyl 2-cyanoacrylate adhesives;<sup>3,40</sup> allantoic membrane;<sup>30</sup> amnioplastin;<sup>10,30</sup> autologous grafts;<sup>10,18,39,41</sup> Cargile membrane;<sup>10,30</sup> cat gut;<sup>10</sup> collagen;<sup>17,18,21</sup> dura-lyophilized human cadaver;<sup>1,15,22,23,28,32,35</sup> fibrin film, adhesive sealant;<sup>4,9</sup> Gelfoam (gelatin film);<sup>8</sup> polyvinyl alcohol film;<sup>30</sup> Vicryl (polygalactin 910) mesh.<sup>24</sup>

Inflammatory response, encapsulating neomembrane, and meningocerebral adhesions are associated with: cellophane;<sup>10</sup> celluloid;<sup>29</sup> Marlex (polypropylene mesh)—simulation of meningioma;<sup>12</sup> metals;<sup>6,10,25,30</sup> rubber;<sup>25</sup> Silastic—subdural hematoma simulating recurrent tumor, subarachnoid hemorrhage;<sup>2,5,12,21,27,33,36</sup> Teflon cloth coated with methyl 2-cyanoacrylate adhesive;<sup>3</sup> Vinyon-N.<sup>16,37</sup>

Inflammatory response and encapsulation are associated with: polyethylene;<sup>8</sup> nylon.<sup>16</sup>

Meningocerebral adhesions are associated with: mica;<sup>10</sup> Orlon;<sup>16</sup> polyvinyl sponge.<sup>13</sup>

Loose connective tissue surrounding film is associated with: Tecoflex EG85 resin;<sup>33</sup> L.R. Resin (polysiloxane-carbonate copolymer).<sup>33</sup>

## References

1. Abbott WM, Dupree EL Jr: Clinical results of lyophilized human cadaver dura transplantation. **J Neurosurg** **34**:770-773, 1971
2. Adegbite AB, Paine KWE, Rozdilsky B: The role of neomembranes in formation of hematoma around Silastic dura substitute. Case report. **J Neurosurg** **58**:295-297, 1983
3. Albin MS, D'Agostino AN, White RJ, et al: Nonsuture sealing of a dural substitute utilizing a plastic adhesive, methyl 2-cyanoacrylate. **J Neurosurg** **19**:545-550, 1962
4. Bailey OT, Ingraham FD: Chemical, clinical, and immunological studies on the products of human plasma fractionation. XXII. Fibrin films in neurosurgery with special reference to their use in the repair of dural defects and in the prevention of meningocerebral adhesions. **J Clin Invest** **23**:597-600, 1944
5. Banerjee T, Meagher JN, Hunt WE: Unusual complications with use of Silastic dural substitute. **Am Surg** **40**:434-437, 1974
6. Beach HHA: Gold foil in cerebral surgery. **Boston Med Surg J** **126**:281-282, 1897
7. Bergethon PR, Trinkaus-Randall V, Franzblau C: Modified hydroxyethylmethacrylate hydrogels as a modelling tool for the study of cell-substratum interactions. **J Cell Sci** **92**:111-121, 1989
8. Busch E, Bing J, Hansen EH: Gelatine and polythene film as dura substitutes and polythene plates as bone substitutes in skull defects. **Acta Chir Scand** **97**:410-416, 1948
9. Cain JE Jr, Rosenthal HG, Broom MJ, et al: Quantification of leakage pressures after durotomy repairs in the canine. **Spine** **15**:969-970, 1990
10. Chao Y, Humphreys S, Penfield W: A new method of preventing adhesions. The use of amnioplastin after craniotomy. **Br Med J** **1**:517-519, 1940
11. Civerchia-Perez L, Faris B, LaPointe G, et al: Use of collagen-

- hydroxyethylmethacrylate hydrogels for cell growth. **Proc Natl Acad Sci USA** **77**:2064–2068, 1980
12. Cohen AR, Aleksic S, Ransohoff J: Inflammatory reaction to synthetic dural substitute. Case report. **J Neurosurg** **70**: 633–635, 1989
  13. Dodge HW Jr, Grindlay JH, Craig WM, et al: Use of polyvinyl sponge in neurosurgery. **J Neurosurg** **11**:258–261, 1954
  14. Friede RL, Schachenmayr W: The origin of subdural neomembranes. II. Fine structure of neomembranes. **Am J Pathol** **92**: 69–82, 1978
  15. Gummerlock MK, Kaufman HH, Narayan RK: FDA panel discussion on cadaver dura. **J Neurosurg** **73**:310, 1990 (Letter)
  16. Huertas J: The use of Orlon for dural replacement. **J Neurosurg** **12**:550–554, 1955
  17. Jannetta PJ, Whayne TF Jr: Formaldehyde-treated, regenerated collagen film and film-laminate as a substitute for dura mater. **Surg Forum** **16**:435–437, 1965
  18. Kline DG: Dural replacement with resorbable collagen. **Arch Surg** **91**:924–929, 1965
  19. Lear M, Harvey SC: The regeneration of the meninges. **Ann Surg** **80**:536–544, 1924
  20. Leary T, Edwards EA: The subdural space and its linings. **Arch Neurol Psychiatry** **29**:691–701, 1933
  21. Lee JF, Odom GL, Tindall GT: Experimental evaluation of silicone-coated Dacron and collagen fabric-film laminate as dural substitutes. **J Neurosurg** **27**:558–564, 1967
  22. MacFarlane M, Symon L: Lyophilised dura mater: experimental implantation and extended clinical neurosurgical use. **J Neurol Neurosurg Psychiatry** **42**:854–858, 1979
  23. Mason MS, Raaf J: Homologous dura mater grafts. An experimental study and clinical evaluation. **Ann Surg** **153**:423–432, 1961
  24. Maurer PK, McDonald JV: Vicryl (polyglactin 910) mesh as a dural substitute. **J Neurosurg** **63**:448–452, 1985
  25. McCosh AJ: The surgical treatment of epilepsy, with a report of fourteen cases. **Am J Med Sci** **115**:549–573, 1898
  26. Nolte J: **The Human Brain: An Introduction To Its Functional Anatomy**. St. Louis: CV Mosby, 1988
  27. Ongkiko CM Jr, Keller JT, Mayfield FH, et al: An unusual complication of Dura film as a dural substitute. Report of two cases. **J Neurosurg** **60**:1076–1079, 1984
  28. Penar PL, Prichard JW: Jakob-Creutzfeldt disease associated with cadaveric dura. **J Neurosurg** **67**:149, 1987 (Letter)
  29. Penfield WG: Meningocerebral adhesions. A histological study of the results of cerebral incision and cranioplasty. **Surg Gynecol Obstet** **39**:803–810, 1924
  30. Pudenz RH, Odom GL: Meningocerebral adhesions. An experimental study of the effect of human amniotic membrane, amnioplastin, beef allantoic membrane, cargile membrane, tantalum foil, and polyvinyl alcohol films. **Surgery** **12**:318–344, 1942
  31. Refojo MF: A critical review of properties and applications of soft hydrogel contact lenses. **Surv Ophthalmol** **16**:233–246, 1972
  32. Rosomoff HL: Ethylene oxide sterilized, freeze-dried dura mater for the repair of pachymeningeal defects. **J Neurosurg** **16**:197–208, 1959
  33. Sakas DE, Charnvise K, Borges LF, et al: Biologically inert synthetic dural substitutes. Appraisal of medical-grade aliphatic polyurethane and a polysiloxane-carbonate block copolymer. **J Neurosurg** **73**:936–941, 1990
  34. Sayad WY, Harvey SC: The regeneration of the meninges. The dura mater. **Ann Surg** **77**:129–141, 1923
  35. Sharkey PC, Usher FC, Robertson RCL, et al: Lyophilized human dura mater as a dural substitute. **J Neurosurg** **15**: 192–198, 1958
  36. Simpson D, Robson A: Recurrent subarachnoid bleeding in association with dural substitution. Report of three cases. **J Neurosurg** **60**:408–409, 1984
  37. Teng P, Feigin I: Vinyon “N” as a dural substitute. An experimental study in the monkey. **J Neurosurg** **12**:591–600, 1955
  38. Teng P, Papatheodorou C: The use of Teflon as a dural substitute and its other neurosurgical applications. **J Neurol Neurosurg Psychiatry** **26**:244–248, 1963
  39. Thammavaram KV, Benzel EC, Kesterson L: Fascia lata graft as a dural substitute in neurosurgery. **South Med J** **83**: 634–636, 1990
  40. VanderArk GD, Pitkethly DT, Ducker TB, et al: Repair of cerebrospinal fluid fistulas using a tissue adhesive. **J Neurosurg** **33**:151–155, 1970
  41. Wallace PB, Meirowsky AM: The repair of dural defects by graft. An analysis of 540 penetrating wounds of the brain incurred in the Korean War. **Ann Surg** **151**:174–180, 1960
  42. Wheeler PR, Burkitt HG, Daniels V: **Functional Histology: A Text and Colour Atlas, ed 2**. New York: Churchill Livingstone, 1987

Manuscript received August 22, 1994.

Accepted in final form May 3, 1995.

Address reprint requests to: Edward L. Spatz, M.D., Department of Neurosurgery, Boston University School of Medicine, 80 East Newton Street, Boston, Massachusetts 02118.