Lamination for Subdermal Implant Fixation

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Abstract: Thirty-six aluminum oxide laminated discs were implanted into 12 young rabbits (18 with a 0.5-mm porous layer and 18 with 1 mm) to determine whether implants that are porous only on one side could fixate to subcutaneous tissue. After 3 months, discs were encased within thin pouches (0.02–0.14 mm) of fibrous connective tissue, as would have been expected of a completely porous implant. Solid sides showed no, while the porous sides showed little, attachment to pouches. Forty-seven percentage (17) of the discs had moved 1.4 ± 0.8 cm beyond the 4.7 + 1 cm they had moved due to normal skin growth, while two others had moved between 6.2 and 6.5 cm beyond this measure. The proportion of 1 mm porous layer discs migrating within subcutaneous tissue was no greater than the proportion of 0.5 mm layer discs migrating ($p = 0.15$). Porous layer height and disc migration did not affect the attachment strength of pouch to surrounding tissues (68 ± 23 N, $p = 0.34$). Pouch thickness, which has been associated to the level of applied forces in other studies, increased with migration distance ($p = 0.054$). Results indicate that one-sided porous discs are likely easier to retrieve than completely porous ones, but cannot be prevented from migrating in loose tissue of young animals. Data is being used to design subdermal radio frequency devices for endangered marine animals. © 2009 Wiley Periodicals, Inc. J Biomed Mater Res Part B: Appl Biomater 91B: 17–25, 2009

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INTRODUCTION

Biotelemetry is increasingly being used to monitor the movements and behavior of wildlife,[1] but has been limited by the difficulties associated with attaching microprocessors to animals and recovering data from the devices for extended periods of time. This is particularly true for marine mammals that annually molt hair or slough skin, and have fusiforme bodies that prevent attaching devices using collars and harnesses.[2] Implantation is the only means of collecting long-term detailed information about the movements, behaviors, and survival of individual animals.[3,4] Such information on the young is particularly lacking.

In a recent study, radio transmitters were implanted into harbor seal pups after making a 6–8 cm deep incision and a 3-cm incision into the underlying blubber in the dorsal thorax.[4] The devices were either cylindrical (approximately 6–8 cm long by 2 cm in diameter) or rectangular (approximately 5–8 cm long × 2.5 cm wide × approximately 1 cm wide). Wound healing, tag adherence to surrounding tissue, and tag signal range results were variable and difficult to explain due to the small sample sizes. Surgery time ranged up to 73 minutes, which is long considering the challenges of operating on wild animals in the field. Further improvements in the design of implanted transmitters (smaller size, tissue fixation, and reliable outputs) are needed to collect movement data of animals to understand the declines of seals and sea lions in Alaska,[5] and to ensure the conservation of endangered species elsewhere in the world.

This research that is being reported herein is part of an overall project relating to the development of a tapered flat RF device with overall dimensions of 5.8 cm × 3 cm × 0.3–0.64 cm for implantation under the cranial skin (which is approximately 2 mm thick[6]), behind the occipital crest of 3-month-old sea lion pups. The size and flat shape will permit shallow and quick insertions, few sutures, and leave no obvious obtrusions on the body. Shallow incisions cause minimal collateral damage and heal rapidly.[7] This

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implantation site is expected to be the most protected against impact and occlusion by other animals, and it changes little over time.[8]

For the well being of the animal and RF considerations, the tag must not migrate. Implant migration is still problematic in many application areas.[9–11] Completely porous biomaterials have promoted implant adherence to soft tissues including the subcutaneous tissue of loose-skinned animals.[12,13] Completely porous materials have also produced milder bioreactions than have solid biomaterials.[12] Ideal thickness of the porous biomaterials is not known; thicknesses have ranged from 2 to 6 mm.[14,15] Porous biomaterials are not as strong as their solid counterparts (which tend to move freely in surrounding tissue).[12,16]

Due to the properties of porous biomaterials, manufacturing costs, and the need for a strong housing, a laminated top lid (thin porous aluminum oxide layer over a thicker solid layer) and a completely solid aluminum oxide (alumina) base was considered for the housing design. For implant adherence to surrounding tissues, porous materials were considered over suturing the implant in place because of time constraints and the observation that suturing has resulted in wound healing issues in other species.[4,16] For strength and housing size restrictions, the porous layer must be as thin as possible. Tissue adherence to laminated materials having both solid and porous sides have previously been examined, but the situation in these investigations, unlike the present situation, was that each side of the implant was in contact with different types of tissue.[17] To finalize the housing design, it was, therefore, crucial to know whether a flat housing having one porous side is biocompatible and capable of adhering to subdermal tissues, and how thick the porous layer should be.

MATERIALS AND METHODS

Alumina discs were manufactured and characterized for pore size and porosity. Then, they were implanted into 12 test animals. Tissue fixation to the discs was measured after 3 months because a cellular steady state around the implants is reached in that time period.[18] Some of the discs (one per animal) were removed for histological examination (evidence of biocompatibility and tissue fixation to disc), while the remaining discs were used to determine attachment strength of the discs to surrounding tissues.

Manufacturing of Alumina Samples

Alumina discs were fabricated using standard 99.5% Al_2O_3 and an average particle size of 57 μm (LECO Corporation, St. Joseph, MI). An organic binder (6.7 wt % polyethylene glycol and polyvinyl alcohol mixture) was used to improve adhesiveness of the alumina particles and burns out of the material at approximately 200–300°C during sintering. Following a cold axial pressing method, a hand press was used to compress the powder in a mold that was manufactured using a high strength 4140 steel. To make the porous structure, 99.99% graphite (caught between 100 mesh and 300 mesh, 496588, Sigma-Aldrich, Oakville, ON) was mixed into the alumina powder at a specific weight percent.[19–21]

Two sets of alumina powders were prepared to create the two layers of solid and porous alumina. The first set was alumina mixed in with the organic binder and the second set was alumina powder mixed with graphite and the organic binder. To produce the bilayered structure; first the alumina-graphite powder mixture was placed in the mold and flattened using the mold die. Then the pure alumina powder was placed on top of the alumina-graphite powder mixture in the mold. The resulting overall thickness of the implants was 4 mm with half the discs having a 0.5-mm thick porous layer and the remaining having a 1-mm thick porous layer. The resulting disc diameter was 17.5 mm. The materials were then pressed and finally sintered to 1400°C (the maximum limit for the available ovens) for 2–3 hours. The atmosphere of the oven was air. Vacuum was initially considered, but it was found not to be necessary.

The alumina powder without graphite was able to densify to produce a layer containing pores that were too small to promote tissue ingrowth [Figure 1(a)]. The alumina powder mixed with graphite was not able to sinter to the same degree due to the presence of large pores. Large pores are created by carbon removal which prevents powder from reaching the same density as the pure alumina layer, thus, causing the porous layer to bulge outwards from the solid layer. To achieve a more uniform section, the edges were sanded using silica paper. After trying different weight percents, a 20 wt % graphite alumina mixture was selected to give an apparently connected porous structure [Figure 1(b)].

High-resolution SEM images were used to measure pore size [Figure 1(b)]. The discs were divided into four sections, and five to seven measurements of pore length were taken per section using a measuring system attached to the SEM. Images having at least two pores greater than 10 μm (smallest pore size) were selected for sampling. Pore volume was measured hydrostatically using distilled water on six discs as in Pavese et al.[21] Density of the alumina powder was assumed to be 3.96 kg M^{-3}. The final average pore size in the apparently open structure was 32.8 $\pm$ 15.4 μm with an associated 35% porosity [Figure 1(c)]. This porosity was acceptable as it provides more mechanical strength than larger ones. The pore size and porosity are, also, acceptable for soft-tissue ingrowth.[22] In a ceramic having an open porosity structure, small pores, such as the ones obtained, would provide more opportunities for interconnections than would larger pores in a ceramic of equal porosity. Additional porous interconnections provided a framework for enhancing tissue ingrowth and fixation. The added porosity made the porous layer, however, weaker than the solid layer.

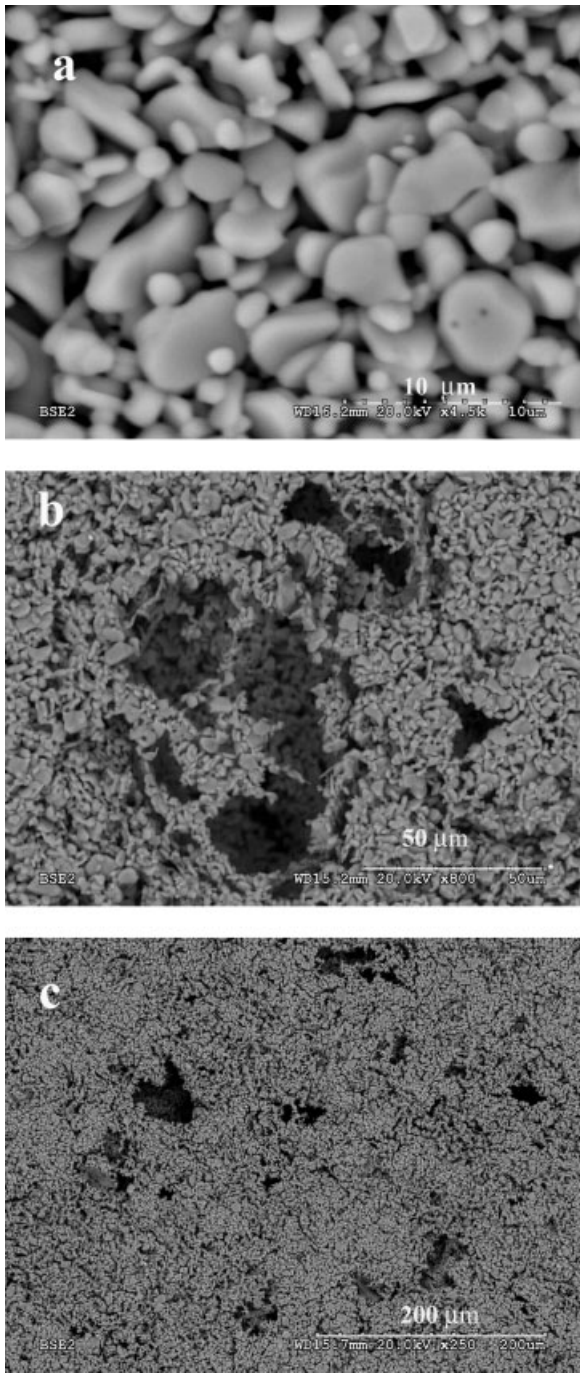

Figure 1. High-magnification SEM views of a laminated disc. (a) denser solid side. (b) and (c) Porous side. A micron bar is at the bottom of each image.

Surgical Procedures

For implantation, twelve 3-month-old female New Zealand white rabbits (Charles River, Canada) were used with an average weight of 2.45 ± 0.22 kg. Rabbits were used instead of sea lions for several reasons: One, ethical practice suggests the use of domestic animals over wild animals and especially young ones for preliminary testing.[23] Obtaining a sufficient sample size of wild animals would have been impossible. Loose-skinned animals like the rabbit and dog have been used to investigate implant adherence and migration in subcutaneous tissue.[13] Loose-skinned animals are a more suitable model than other animals for young pinnipeds (seals and sea lions) because the skin (connective tissue and vascular network) as well as the underlying blubber layer of young pinnipeds are poorly developed and thin.[24] Finally, rats and rabbits are suggested for use for preliminary testing in established testing procedures.[18] The use of rabbits over sea lions was approved by the Animal Care Committee of the University of British Columbia, and care was in accordance with the guidelines of the Canadian Council on Animal Care.

Discs and not the final housing were tested because the housing for the RF housing was too large for the rabbits. The effect of implant shape has been documented,[25,26] and it has been suggested that acute angles in implants be avoided, and that tubular or rounded implant designs are optimal. This advice was followed in the housing and disc design. Disc and housing were of similar thickness, as results indicated that thinner implant samples resulted in thinner fibrous capsules.[27]

Four rabbits were implanted on a given day, and the experimental periods were 98, 105, and 111 days. Staggered dates were chosen so that the experiments could be discontinued if complications arose such as infections or strong foreign body reactions to the implants. In each rabbit, four implantation sites were identified on the rabbit back. One site was used as the control, which consisted of an incision, the formation of a pocket under the skin and suture. In each rabbit, one alumina disc with a porous layer of 0.5 mm, one disc with a porous layer of 1 mm, and a second disc of either 1 mm or 0.5 mm porous layer were implanted using a randomization block design. The second disc and the control were for histological examination. The discs, which were not used for the examination, were used for measuring tissue attachment strength.

Before surgery, the dorsal thorax was shaved and disinfected. Implants were sterilized using an autoclave. Rabbits were sedated with Ketamine (Ketalean®, Bimeda MTC, Cambridge, ON) 35 mg/kg and Xylazine (Rompun®, Bayer, Toronto, ON) 5 mg/kg intramuscularly. Surgical anesthesia was maintained with Isoflurane (Aerrane®, Baxter, ON)(2–3%) via facemask. To maintain a consistent implant location within each rabbit, a template was used and referenced to the dorsal spinous process of the second thoracic vertebrae. The template allowed four incisions to be made, two on either side of the spine, at least 4 cm from any other incision. Incisions were made caudal to the template locations and the sterile implants were inserted cranially into a subcutaneous tissue pocket made by blunt dissection. The pockets were approximately twice the length of the implants (Figure 2). Initially it was planned to insert the discs just below the dermis. On all but three occasions, however, the cutaneous trunci muscle did not easily separate from the skin layer, so in keeping the surgery

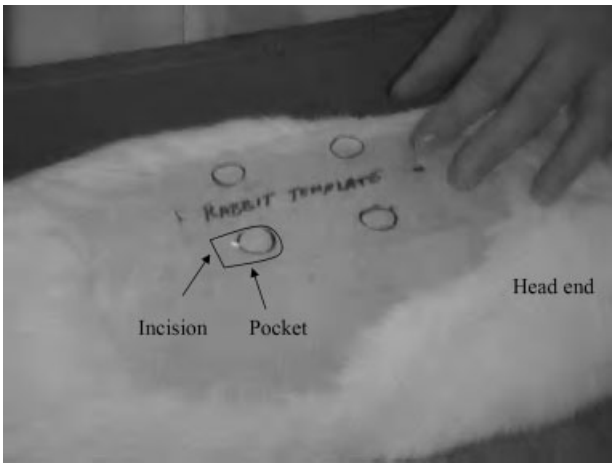

Figure 2. Four discs were implanted subdermally in the dorsal thorax. The pockets were approximately twice the length of the implants.

minimally invasive as was stipulated in the animal care protocol, most of the implants were placed just below this thin muscle. For the subcutaneous implants that were surrounded by the same type of tissue, direction of porous layer was randomized. For the three subdermal implants, discs were oriented with the pore layer facing the epidermis. In the first four rabbits, the skin in the middle of the disc was tattooed to measure tissue growth away from the original implant site.

The wounds were closed using sutures. Suture patterns were changed from skin sutures to subcutaneous sutures after one rabbit in the first set attempted to remove the sutures (no obvious effect on wound healing). Postoperatively rabbits were given the analgesic Butorphanol (Torbegesic®, Wyeth, ON) (0.2 mg/kg) twice daily and Enrofloxacin (Baytril®, Bayer, ON) (5 mg/kg) intramuscularly once daily for 5 days. After surgery, rabbits were bandaged, placed in groups in an indoor/outdoor pen, and allowed to move unrestricted.

After the 3-month experimental period, the animals were killed by administering Ketamine (35 mg/kg) and Xylazine (5 mg/kg) intramuscularly followed by pentobarbital (Euthanyl, Vetoquinol, ON) (120 mg/kg) via an ear vein. The backs of the rabbits were then shaved, and areas for extraction were marked.

Measuring Biocompatibility and Tissue Fixation

Histology. Square blocks of tissue were extracted (2.54 cm × 2.54 cm) and placed in 10% buffered formalin for fixation and sent for histological examination. Fixed skin samples were examined grossly, the implanted discs were removed, and cross-sections were made of the skin through the area in which the discs were located, or, in control samples, through the middle of the submitted tissue sample. All trimmed samples were placed in tissue cassettes, processed into paraffin blocks, sectioned at 5 μm, stained with hematoxylin and eosin stain, and mounted on glass slides using standard techniques. The amount of pigment was assessed on a 5-point scale and also recorded for each sample in a tabular form.

Slides were examined and each section of tissue was either recorded as normal, or a description was made of any abnormalities. Measurements recorded included the number of inflammatory cells present on both smooth and porous surfaces; the presence and distance of blood vessels to surface of the discs; the density of capillaries and vessels near discs; the area of fibrous tissue around the disc in contact with the host tissue; the thickness of the encapsulating pouch, and the degree of tissue penetration by examination of implant cross sections. The average pouch thickness was measured at four representative sites. As an indicator of biocompatibility and implant integration into host tissue, the type of tissue around the pouch was determined. *T*-tests were used to examine the effect of porous layer thickness on the variables mentioned in the above paragraph.

Pullout Attachment Strength. The procedure that was used to measure tissue detachment strength of synthetic implants relied on a digital force gauge (DPS-110, Imada Inc., Northbrook, IL) to determine the force required to remove a disc from its surroundings following a method described in Ref. 28. Before performing the pullout tests, a ventral incision to the implant location was made to access the implant. Discs were not adhering to the same type of tissue or in the same way (two were completely free). Pullout strengths were, therefore, grouped according to similar adherent tissue. The rabbit carcasses were placed on a test stand (LV-220, Imada Inc., Northbrook, IL) below the force gauge. Grips (SC-8, Imada Inc, Northbrook, IL) attached to the force gauge, were used to clamp onto the implants. The discs were extracted out of entire animals instead of excised sections as in Ref. 29 because the subcutaneous tissue where the discs were embedded is capable, due to its elastic nature, of being highly stretched. Sections would have set limits on this flexibility. Previously recorded implant extractions forces have ranged from 10 to 90 N.[17,28,29] For such low forces, it was not necessary to have special clamping devices for holding down the carcasses during the pullout tests. During the extractions, two people easily held down the carcass while each disc was extracted upwards out of the carcass using a manually operated cross head attached to the force gauge. A laptop computer was connected to the force gauge using a RS-232 cable (CB-203, Imada Inc. Northbrook, IL), and data were recorded using a terminal program called Simpleterm Gold (Ptronix). Data from the force gauge was queried 20 times per second.

Implant Movement Tracking. Average skin tissue growth was measured as the distance from the original location of implantation (as indicated by the implant template aligned to the spinal position) to the final location of

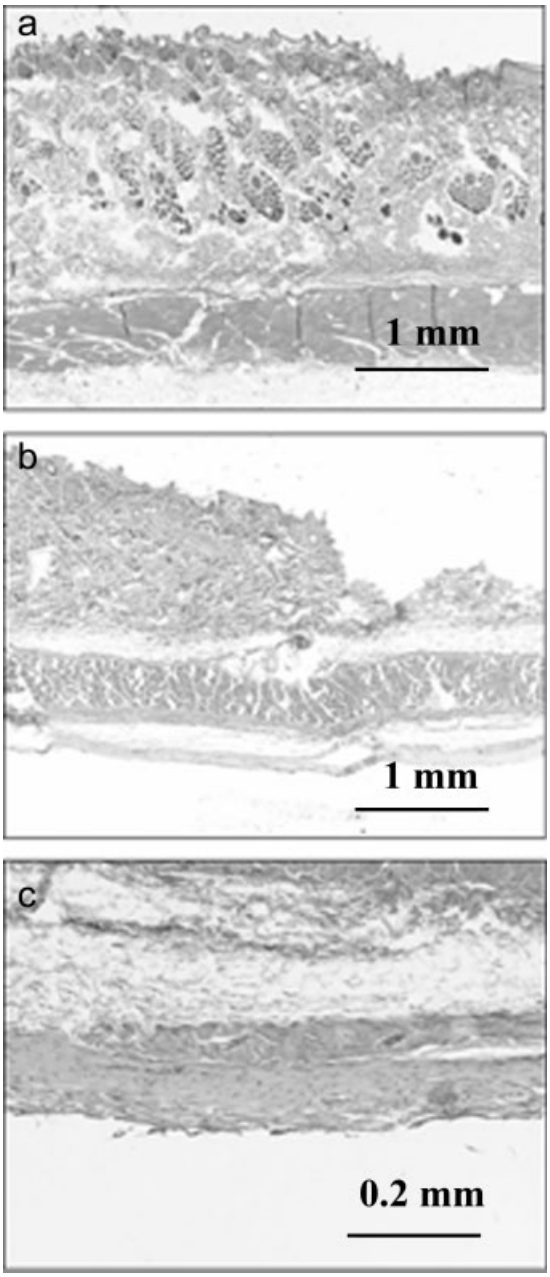

Figure 3. Comparative pictures of cross-section through (a) the control region showing dermis with muscle below it, (b) an implant region showing dermis with muscle below it and implant location at the bottom, and (c) an implant region showing the implant location at the bottom below the pouch. A millimeter bar is at the bottom of each image.

the tattoos. Disc migration was calculated as movement beyond the average movement caused by normal skin growth plus 1 cm. The 1 cm allowance was due to the larger gap caused by making incisions and applying force onto the subcutaneous tissue of loose-skinned animals.[7,30]

The Fisher's exact test was used to examine if more discs of one porous layer height migrated more frequently than discs of the other height. Two-factor ANOVA was used to determine if migration and porous layer height affected tissue attachment strength. Regression analyses were carried out to determine if there were relationships between migration and other measured variables, and analysis of variance tests were carried out to determine if slopes were significantly different from zero.[31]

RESULTS

Biocompatibility

The rabbits gained an average of 1.85 kg (75% weight increase) following surgery. This increase is comparative to increases found in other studies.[32,33] In the gross tissue histological examination, all alumina discs exhibited good biocompatibility. All control sections were anatomically normal with no evidence of inflammation or foreign body reaction (Figure 3). Each disc was located in a well-vascularized pouch of connective tissue (Figure 3). The connective tissue and supportive blood vessels had adhered to the pouch and surface of the implants. In most discs, minor surface erosion of the porous disc surface was observed (Table I). Outside of the porous layer, crystalline debris was evident in the collagenous interstitium between fibrocytes. This material was being picked up and removed by the phagocytic system. This reaction was considered mild.

The histopathologic examination revealed a well-defined wall of mature fibrous connective tissue around each disc forming a collagenous pouch or capsule for the implant. The connective tissue grew into the porous, but not the smooth surface of the discs. This pouch wall generally varied between 5 and 10 fibrocytes in thickness. The thickness of the pouch wall varied from 20 to 140 μm (Table I). There was no apparent association between porous layer height and pouch wall thickness or between porous layer

TABLE I. Observations on Pouch Wall Thickness, Amount of Crystalline Debris, and Pouch Attachment to Disc as Measured by the Degree of Tissue Penetration Into the Disc

Rabbit ID	Pouch Wall Thickness (mm)	Attachment to Disc	Amount of Crystalline Debris[a]
1	0.10	None	4
2	0.14	None	2
3	0.07	Closely attached	5
4	0.02	Very close attachment	2
5	0.08	Very close attachment	4
6	0.07	Attachment	4
7	0.05	Slight attachment	4
8	0.08	None	4
9	0.02	None	3
10	0.07	Slight attachment	3
11	0.08	None	2
12	0.09	Slight attachment	2

[a] 0 = No debris, 1 $\leq$ one crystal per 200 $\times$ field, 2 = crystalline material arranged linearly but not continuously adjacent to the wall of the pouch, 3 = continuous crystalline material on or adjacent to the pouch wall, 4 = crystalline material in focal masses of macrophages or giant cells scattered in the subcutis, and 5 = large, continuous masses of cells and crystals.

TABLE II. Skin Growth Movement Tracked Using a Tattoo Marker on the Skin of Four Rabbits

	Rabbit 1	Rabbit 2	Rabbit 3	Rabbit 4
Upper-right	6.6 CV	4.5 CV	2.5 V	4.5 CV
Lower-right	7.4 CV	4 CV	4.5 V	4 C
Lower-left	6.9 C	4.2 V	4.5 V	4 C
Upper-left	7.2 C	3.8 C	2.5 V	4 C
Total mean movement	–	4.7 cm		
Standard deviation	–	1.5 cm		

The mean migration distance was used to adjust implant migration distance. CV, caudal ventral; C, caudal; V, ventral.

height and amount of crystalline debris (*t*-test, degree of freedom (d*f*) = 10; *t*-statistic (*t*) = 0.6, probability (*p*) = 0.56 and $t = 0.26$, $p = 0.79$, respectively).

Tissue Fixation

Implant Movement. The tattoos on the skin moved in the caudal-ventral direction 4.7 cm from the incision sites (Table II). Nineteen discs migrated an average of 1.9 ± 1.8 cm beyond this distance plus the 1 cm allowance. Seven of the 12 discs sent for histology migrated. The three that had been inserted right under the dermal layer adhered to their insertion points. The proportion of discs of porous height 1 mm migrating within subcutaneous tissue was no greater than the proportion of discs of porous height 0.5 migrating (Fisher Exact test, sample size (*n*) = 33, $p = 0.15$; the three subdermally implanted discs were not part of this analysis).

No differences between migrated and nonmigrated discs in regard to pouch thickness and the amount of crystalline debris present were found (*t*-test, d*f* = 10; $t = 0.47$, $p = 0.64$, and $t = 0.1.28$, $p = 0.23$, respectively). Of the discs that did migrate, however, pouch thickness increased with migration distance (Figure 4, ANOVA d*f* = 6, *f*-statistic (*f*) = 6.29, $p = 0.054$).

Histology Data Relating to Tissue Fixation. The attachment of the fibrous pouch to the disc surface was described using a ranking scale (0 = none, 4 = close attachment) (Table I). Tissue attachment was compared for different porous layer heights, and no statistical difference for tissue attachment was observed (*t*-test, d*f* = 10, $t = 0.47$, $p = 0.64$). No correlation existed between this measure and tag migration, and there was no difference between this measure for migrated and nonmigrated tags (*t*-test, d*f* = 10, $t = 1.01$, $p = 0.33$). The degree of attachment of the pouch to the disc for eight of the 12 pouches was slight or zero (five were observed not to be attached).

Pullout Attachment Strength. Pouches surrounding the discs were positioned in one of three ways during the pullout tests on 24 discs, namely (A) firmly attached to the dermis ($n = 3$); (B) loosely attached within loose connective tissue ($n = 2$), and (C) attached to subcutaneous tissue ($n = 19$). In case A, failure was caused by disc separating (shearing) from its pouch. At failure, the pouch remained completely attached to surrounding tissues, so the attachment strength of surrounding tissues was not determined. In this case, pouches could be said to be more tightly attached to surrounding tissue than to the discs. In case B, the disc complete with its pouch were nearly free within areolar tissue. In case C, attachment failure was most often caused by breakage of the tissue attached to the pouch (not at the tissue/pouch interface). As the disc was being pulled out, the elastic-like surrounding areolar tissue was in tension. Pore layer height and migration did not affect peak attachment force (strength) (ANOVA, d*f* = 11, $f = 1.2$, $p = 0.34$). Peak attachment strength was 68 ± 23 N.

DISCUSSION

In this study, no adverse tissue reaction for aluminum oxide laminates in growing animals was observed. Resulting encapsulation thickness and pouch tissue were very thin and similar to completely porous implants.[34,35] This result indicates that the degree of biocompatibility of laminated discs and completely porous discs are similar.

The variation in pouch thickness was the same for migrating and nonmigrating discs. In other studies, pouch thickening had been associated with forces acting on the implant.[36–38] In this study, the nonporous side of a disc would have rubbed against the adjacent nonattached pouch whenever the skin above it moved while normally growing or contracting (Figure 5). This friction resulting from random movements likely caused most of the variation in pouch thickness.

Completely porous discs subcutaneously inserted into loosed-skinned animals have not been observed to migrate, while many of the laminated discs in this study did.[13] To migrate, a force must have been applied onto the disc that equaled the low attachment force of 68 ± 23 N plus the additional force required to forcedly move the disc plus its pouch to a new location through the loose connective tissue below the dermis (Figure. 5). Forces relating to normal

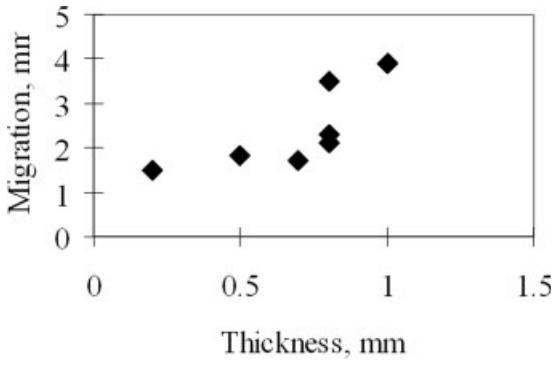

Figure 4. Relationship between implant migration and pouch thickness ($f_{(1,6)} = 6.29$, $p = 0.054$).

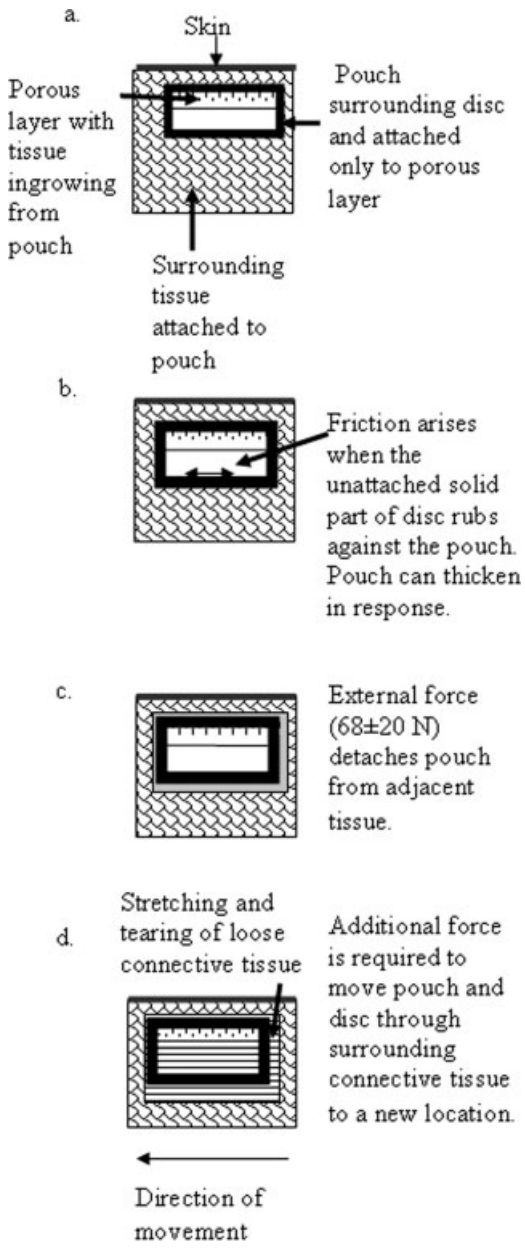

Figure 5. Schematics of a porous disc and interactions with surrounding cell and exterior environments.

back scratching during the experimental period are likely of the level required to cause migration. Long migrations would not have required higher exterior force levels than shorter migrations would have required if lower disc attachment strengths had been in association with longer migrations. Attachment strengths in this study did not, however, vary with migration distance. Migration distance was, therefore, most likely related to the level of the applied force. In addition, the positive relationship between migration distance and pouch thickness for migrating discs found in this study (Figure 4) indicates that the level of that applied force increased with pouch thickness. The experimental data and forces involved in migration suggest that laminated discs are more likely than completely porous ones to migrate because tissue movements against the solid side of the laminated discs that eventually lead to pouch thickening are capable of being sensed by an animal, and if sensed, the animal responds by scratching hardest on the pouches that had experienced the highest level of tissue movement.

The results indicate that most likely porous material should cover a solid base as well as the solid lid of the housing to prevent its migration under the skin of young pinnipeds (seals and sea lions). The porous layer could be at maximum 0.5 mm thick, as there was no effect of porous layer height (0.5 mm or 1 mm) on attachment strength, tissue attachment, or migration. Further studies are needed to define lower limits for thickness.

Results also indicate that, as porous layers break down overtime, laminated discs could easily be removed from the surrounding pouches without causing harm to the animal. Breakdown was evidenced by the crystalline debris that had accumulated only outside of the porous layer and the variability in the degree of pouch attachment to this layer (Table I). The alumina particles deriving from porous layer erosion are not of concern if they remain smaller than 5 μm, because alumina debris of this size can be ingested by macrophages.[39] Laminated housings will permit retrievable data storage devices and other new developments in biotelemetry.

The pull-out disc detachment strengths apparently derived from the stretching and tearing of surrounding sheets of collagen. Under high strains like those that occurred when the discs were pulled out, collagen fibers line up and act like tendons.[40] The pull-out strength matched closely to published implant attachment forces from other studies and tension strength of tendon complexes[40] (Table III). Maximum tension strengths tend to be lower in younger animals as compared with older animals.[41] The attachment strength and failure data obtained in this research can be used to predict how tissue might react to laminated devices in other animals and older animals.

For example, the blubber of older marine mammals is greatly enriched in collagen and elastin fibers as compared with other animals, which makes the blubber firmer,

TABLE III. Tendon and Collagen Tensile Strengths[41]

Tissue	Tensile Breaking Strength (N)	Test Animal
Femur-medial collateral ligament-tibia complex	40	Young rabbit
Ditto	54–123	Immature rabbit
Ditto	30	Rat
Femur-medial anterior cruciate ligament-tibia complex	60	Rat
Collagen	4	Films made from rat
Achilles tendon	240	Rabbit

tougher, and more fibrous than other animals.[42] Marine mammal blubber does not tightly adhere to underlying musculature. Due to these blubber characteristics, it is likely that tissue attachment to a one-sided porous alumina housing (implanted into the blubber just under the tightly adhering skin) would be stronger than those observed for loose-skinned animals. Device migration would also be less likely in older marine mammals.

The research findings contribute to further development of retrievable RF and other devices. In future studies, detailed material characterizations (density, etc.) should be performed before executing extensive animal trials or considering these materials for clinical use.

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