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# United States Patent [19]

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Fournier et al.

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[54] **BIOARTIFICIAL PANCREAS**

[56] **References Cited**

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### U.S. PATENT DOCUMENTS

5,002,661	3/1991	Chick et al.	604/4
5,100,392	3/1992	Orth et al.	604/175
5,116,493	5/1992	Chick et al.	604/4
5,116,494	5/1992	Chick et al.	604/4
5,387,237	2/1995	Fournier et al.	604/4

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[21] Appl. No.: **711,364**

[57] **ABSTRACT**

[22] Filed: **Sep. 3, 1996**

### Related U.S. Application Data

An implantable bioartificial pancreas device having an islet chamber containing glucose responsive and insulin-secreting islets of Langerhans or similar hormone secreting cells, one or more vascularizing chambers open to surrounding tissue, a semi-permeable membrane between the islet and vascularizing chambers that allows passage of small molecules including insulin, oxygen and glucose and does not allow passage of agents of the immune system such as white cells and antibodies, the vascularizing chambers containing a growth factor soaked fibrous or foam matrix having a porosity of about 40 to 95%, the matrix providing small capillary growth and preventing the blood from clotting in the lower chamber.

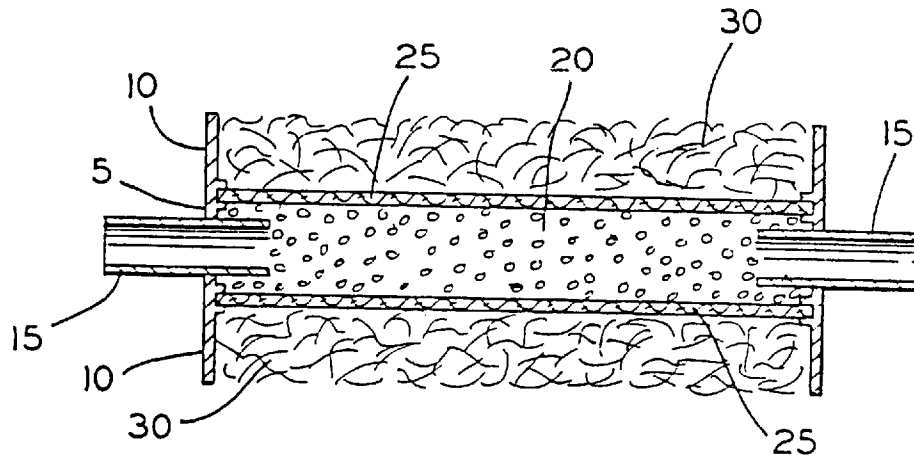
[60] Continuation of Ser. No. 369,708, Jan. 6, 1995, which is a division of Ser. No. 161,172, Dec. 1, 1993, Pat. No. 5,425,764, which is a continuation of Ser. No. 922,562, Jul. 30, 1992, abandoned.

[51] **Int. Cl.<sup>6</sup>** ..... **A61F 2/02; A61F 2/00**

[52] **U.S. Cl.** ..... **623/11; 604/4; 604/175; 424/424**

[58] **Field of Search** ..... **623/11, 12; 604/4, 604/175; 424/424**

**20 Claims, 1 Drawing Sheet**



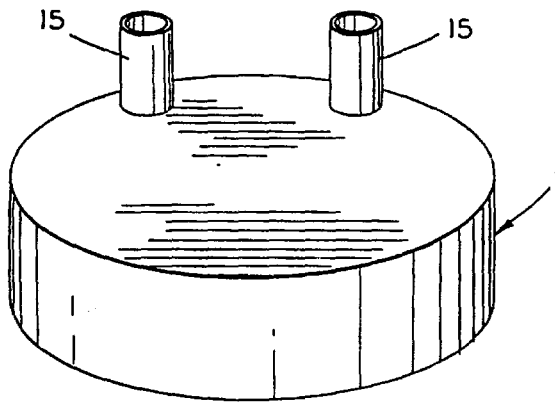


FIG. 1

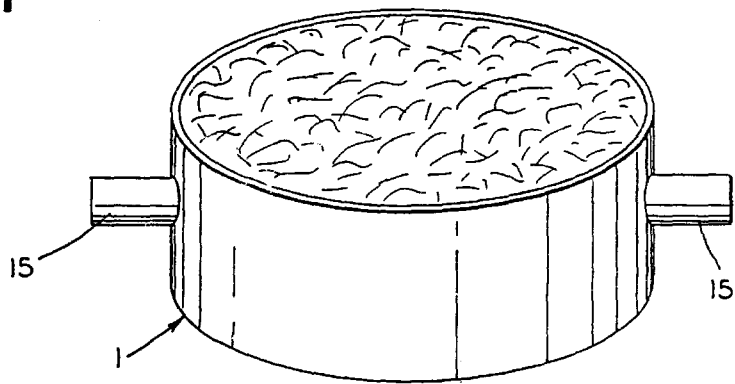


FIG. 2

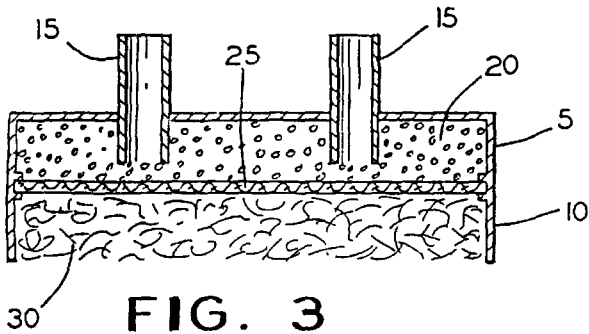


FIG. 3

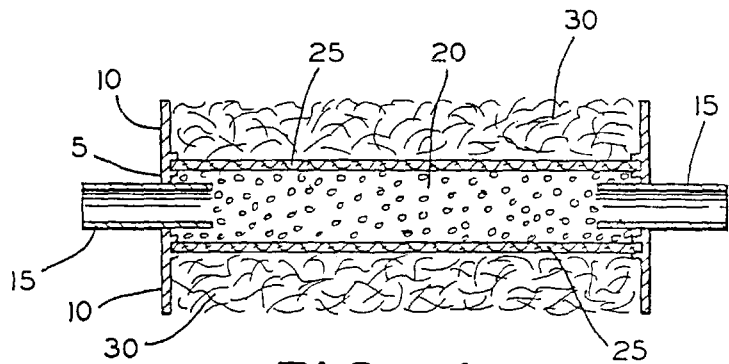


FIG. 4

**BIOARTIFICIAL PANCREAS**

This is a continuation of application Ser. No. 08/369,708, filed on Jan. 6, 1995, which is a Divisional of application Ser. No. 08/161,172, now U.S. Pat. No. 5,425,764 which is a continuation of application Ser. No. 07/922,562, filed Jul. 30, 1992, abandoned, the disclosures of which are hereby incorporated by reference.

**FIELD OF THE INVENTION**

The present invention is directed to a bioartificial implantable pancreas for the treatment of insulin dependent diabetes mellitus.

**BACKGROUND OF THE INVENTION**

There is a need to provide a biocompatible and implantable device containing islets of Langerhans, or the beta cells thereof, that can supply the hormone insulin for the purpose of controlling blood glucose levels in people with diabetes mellitus requiring insulin. Insufficient regulation of blood glucose levels in people with diabetes has been associated with the development of long-term health problems such as kidney disease, blindness, coronary artery disease, stroke, and gangrene resulting in amputation. Therefore, there is a need to replace conventional insulin injections with a device that can provide more precise control of blood glucose levels. An implantable bioartificial pancreas device which was evaluated in dogs by Monaco et al. was recently described in the following articles: "Successful treatment of diabetes with the biohybrid artificial pancreas in dogs" *Transplantation* 51, 43-51, January, 1991; "Biohybrid artificial pancreas: Long-term implantation studies in diabetic, pancreatectomized dogs" *Science* 252, 718-721, May 1991; "Transplantation of islet allografts and xenografts in totally pancreatectomized diabetic dogs using the hybrid artificial pancreas" *Ann. Surg.* 214 339-362 September, 1991. The device described in these articles was a chamber containing a coiled copolymer tubular membrane through which and within which blood flowed. The coiled copolymer tubular membrane had a nominal porosity of 80,000 daltons which permit free passage of nutrients and insulin but inhibit passage of the agents of the immune system (immunoisolation). Surrounding the outside of the coiled tubular membrane and within the chamber were placed islets of Langerhans. The islets of Langerhans are composed primarily of  $\alpha$ ,  $\beta$ ,  $\delta$  and PP cells which synthesize and secrete the hormones glucagon, insulin, somatostatin, and pancreatic polypeptide respectively. These cells may interact in unknown ways to regulate the level of serum glucose. The islets are not in direct contact with the blood. Blood flow through the coiled tube was achieved by connecting the ends of the coiled tube to standard vascular grafts which were then anastomosed to blood vessels. In this type of device blood physically contacts and flows through the artificial coiled copolymer tubular membrane which comprises the device. The major limitation of this approach is the formation of blood clots. There is therefore a need for a device which can provide the islets with a non-clotting blood supply which also provides for rapid transfer of essential nutrients as well as glucose and insulin.

U.S. Pat. No. 4,699,141 (Rhode Island Hospital) discloses a neovascularization approach for transplanting cells by placing a ligated blood vessel in a sponge made of a material that is preferably an acrylic copolymer carrying collagen. This patent is similar to a concept for an "organoid" described later by two Thompson et al. articles, "Site-

directed neovessel formation in vivo" *Science*, 1349-1352 September, 1988 and "Heparin binding growth factor 1 induces the formation of organoid neovascular structures in vivo" *Proc. Nat'l Academy of Science, USA*, 86, 7928-7932, 1989. In these articles blood vessel growth was promoted in vivo within a porous matrix consisting of a Gore-tex brand of polytetrafluoroethylene (PTFE) fibers containing absorbed growth factor. It was shown that the vascularized PTFE material served as a vehicle for the transplantation of hepatocytes in rats. However, the matrix was not used as a bioartificial pancreas and it provided no protection from the recipient's immune system.

U.S. Pat. No. 5,100,392 describes an implantable device for delivering drugs or other liquid solutions through incorporation of the device into the surrounding tissue. One of the features appears to be the use of a hollow tubular casing of a synthetic porous material that promotes growth of connective tissue. Inlet (and outlet) catheters are used to administer the fluid (including islets) directly to and from the vascularized connective tissues.

The alternative embodiment in this patent (5,100,392) for transplanting cells, such as islets of Langerhans, consisting of a plurality of hollow synthetic tubules arranged as a central cylindrical core within the outer casing will result in vascularization of the casing only leaving the tubules containing transplanted cells, such as the islets of Langerhans, either not vascularized or poorly vascularized. Although this poses no real problem for the delivery of drugs or other liquid solutions, in the case of transplanted cells, such as islets, placed within the lumens of the plurality of hollow tubules, this inner core region not being sufficiently vascularized will quickly result in injury and death of the transplanted cells or at best result, for the case of islets as the transplanted cells, in a poor glucose-insulin response with a minimal effect on the level of glucose control in a patient with diabetes mellitus. In the invention presented herein for a bioartificial pancreas, the device geometry is a thin cylindrical disk which results in precise control of the penetration depth of the ingrowing tissue and capillary bed resulting in the transplanted cells, such as the islets of Langerhans, being all at the same uniform distance from the vascularized region of the device. This will result in a more compact and easily implantable device with improved mass transfer characteristics between the transplanted cells and the vascularized region of the device. In the case of a patient with diabetes, the blood glucose control will therefore be normalized.

**OBJECTS OF THE INVENTION**

It is an object of the present invention to provide an easily implantable, easily used bioartificial pancreas device which provides a site-specific natural, non-clotting blood supply to immunoprotected islets of Langerhans and minimizes fibrotic overgrowth and encapsulation.

It is another object of the invention to provide the above described device with an upper chamber containing the islets of Langerhans (islet chamber) or other secreting cells such as neurons, pituitary, parathyroid, liver, adrenal and ovarian and a means for adding and removing them via an inlet and outlet catheter with ports, and a lower chamber (vascularizing chamber) containing a fibrous or sponge-like matrix having a porosity of about 40 to 90 percent, the matrix having an angiogenic stimulating growth factor such as heparin binding growth factor, collagen, endothelial cell growth factor, acidic and basic fibroblast growth factor material and porous openings with average pore size in the

range of 10 to 200 microns to facilitate the growth of the neovessels. The matrix material containing the growth factor stimulates the surrounding tissue of the host to penetrate the matrix and vascularize it much like the process of wound healing, with the result that the device develops its own blood supply after a sufficient period of time, usually within four weeks. The device includes a semipermeable membrane made of any natural or synthetic material providing a molecular weight cut-off of less than 100,000 that is placed between the upper (islet) and lower (vascularizing) chambers to protect the islets of Langerhans from the agents of the host's immune system (immunoisolation) while allowing passage of smaller nutrient molecules such as glucose and oxygen as well as insulin. An extension of this description would include placement of the islets of Langerhans in a central islet chamber which, in one embodiment, is sandwiched between two outer vascularizing chambers containing the growth factor and matrix material, with a means of adding or removing the islets. Semipermeable membranes for immunoprotection of the islets would separate the islets in the central chamber from the outer chambers. Each outer chamber containing the growth factor and matrix would have the same characteristics and functions described above.

It is an object of the present invention to provide a method of using the above bioartificial pancreas device, the method including:

- a) providing the bioartificial pancreas as above described in the preceding objects.;
  - b) making the thickness of the pancreas about 1 to 10 millimeters, its diameter depending on the size, weight, and age of the patient as well as the number of islets needed for effective treatment;
  - c) implanting the pancreas in a mammal; and
  - d) immunoisolating the implanted islets of Langerhans.
- The method also includes:
- e) using islet of Langerhans or the beta cells therefrom obtained from a human pancreas or animal sources such as the pig, cow, dog, or rat or insulin secreting cells either naturally occurring or experimentally derived; and
  - f) a porous support matrix using angiogenic growth factors to stimulate device vascularization which minimizes fibrotic overgrowth and encapsulation.

#### DESCRIPTION OF THE DRAWINGS

These and other objects will be apparent from the specification that follows, the appended claims, and the drawings in which:

FIG. 1 is a perspective view of an implantable bioartificial pancreas;

FIG. 2 is a perspective view of another implantable pancreas having dual matrix layers;

FIG. 3 is a sectional view of the bioartificial pancreas of FIG. 1; and

FIG. 4 is a sectional view of the pancreas of FIG. 2.

#### SUMMARY OF THE INVENTION

The present invention provides an implantable bioartificial pancreas comprising a device having an enclosed islet chamber and one or more vascularizing chambers having an opening at one end thereof that provides access to surrounding tissue; a plurality of insulin-secreting islets of Langerhans in the islet chamber, inlet means for supplying islets to the islet chamber, outlet means for removing islets from the islet chamber, a semi-permeable membrane(s) between the

islet and vascularizing chambers, the membrane(s) providing a molecular weight cut-off less than about 100,000 thereby immunoprotecting the islets from the vascular area within the vascularizing chamber and around the implanted vascularizing chamber, the membrane(s) allowing passage of molecules with molecular weights less than 100,000, including glucose, oxygen and insulin between the islet and vascularizing chambers and not allowing passage of agents of the immune system such as leukocytes, antibodies, and complement to the islet chamber, and a biocompatible fibrous or porous foam matrix in the vascularizing chamber to provide a neovascular formation region for enhancing the growth of small capillaries for providing efficient mass transfer of nutrients and insulin between the islet chamber and the blood stream in the vascularizing chamber, the fibrous or foam matrix having a porosity of about 40 to 95 percent and interconnecting passageways that are equivalent to an open-celled foam having an average pore size of about 10 to 200 microns, the fibers and foam being of an organic or inorganic material, the organic material composed principally of carbon, oxygen, and hydrogen atoms and optionally, nitrogen and sulfur atoms, the inorganic materials being composed of one or more of carbon, titanium, silica, sodium, calcium, strontium, magnesium, zinc and boron atoms.

The present invention also provides a method of presenting insulin-secreting islets of Langerhans to the vascular system of a mammal, the method comprising:

- A. providing a bioartificial pancreas as defined above;
- B. making the thickness of the pancreas about 1 to 10 millimeters; and
- C. implanting the pancreas in a mammal such as in the peritoneal cavity which presents the insulin directly to the liver which is known to be more effective.

#### DETAILS OF THE INVENTION

As seen in the drawings, FIG. 1 and 3, a bioartificial pancreas device 1 comprises an islet-containing upper chamber 5, an open on one end vascularizing lower chamber 10, and inlet and outlet means 15 for supplying islets of Langerhans 20 to the islet containing chamber.

A semi-permeable membrane 25 is provided between the islet and vascularizing chambers. The membrane 25 allows passage of nutrients and small vital molecules including oxygen, glucose and insulin but does not allow passage of agents of the immune system such as white cells and antibodies.

In the embodiment shown in FIGS. 2 and 4, the pancreas device is shown with dual matrix 30 layers, each of the matrix 30 materials being separated from the islets by a membrane 25.

A biocompatible fibrous or foam matrix 30 is provided in the vascularizing chamber, the matrix 30 being growth factor soaked to promote growth of the vascular system including growth of small capillaries.

The matrix 30 generally has a porosity of as low as about 40 to 50 percent and as high as about 90 to 95% percent. The matrix porosity is preferably about 30 to 90 percent. The matrix foam is an open-celled structure and generally has an average pore size of about 10 to 200 microns, the preferred size being about 50 to 100 microns.

Although the islets of Langerhans cells are highly preferred, other cellular transplants can be used that require immunoprotection and that secrete or metabolize a substance that can permeate the membrane 25. The secreted

substances may, for example, be from liver, parathyroid, thyroid, pituitary, neural, adrenal, ovarian or genetically engineered cells. Other useful cells may perform detoxifying functions by removing and metabolizing toxic substances found in the bloodstream.

The fibrous matrix has interconnected openings equivalent in porosity and size openings that are approximately equivalent to the size openings to the foam matrix just described. Hence, the fiber openings are equivalent to the 10 to 200 microns set forth for the foam. The fibers are generally about 10 to 60 or 100 microns in diameter, the preferred average diameter being about 10 to 30 microns.

The total thickness of the matrix is about 1 to 4 mm, the preferred thickness being about 2 to 3 mm. The matrix thickness, thus, is sufficient to absorb proteins, ECM materials, growth factor materials, develop a blood supply, and the matrix also is preferably non-absorbable by the body of the mammal and minimizes fibrotic overgrowth and encapsulation.

Suitable matrix materials are keratin (silk, wool, hair), collagen, of various types, polyolefins such as polyethylene, polypropylene and polybutylene, polyesters such as polyethylene terephthalate and polyethylene adipate, polyurethanes such as polyesterurethanes and polyetherurethanes, glass including glass fibers, stainless steel, silicones, organopolysiloxanes and graphite and combinations thereof. The keratin matrix is keratin, keratin-containing or keratin-like.

The pore size of the highly preferred matrix is at least about 10 microns and optimally 50 to 100 or 120 microns.

For some applications, suitable matrix materials are polyamides including nylon such as polycaprolactam and polyhexamethylene adipate, polyamide-imides, polycarbonates, polyacrylates including polymethyl methacrylate and polyethylmethacrylate and polystyrene.

A suitable fiber and foam matrix is organic or inorganic, the organic material being composed principally of carbon, oxygen, and hydrogen atoms, and optionally nitrogen and/or sulfur atoms. Organic material such as polyolefins, composed of carbon and oxygen atoms are highly useful, such hydrocarbon polymers being non-halogenated and non-fluorinated.

Excellent results have been obtained when the matrix is made of hair in which the average diameter of the hair fiber is about 10 to 15 microns, the fiber length is about ½ to 2 inches, the matrix thickness is about 2 to 3 millimeters and the porosity is about 80 to 85 percent.

In operation after implantation in the peritoneal cavity, or other suitable site, and after a sufficient period of time for device vascularization, usually about four weeks, the islets of Langerhans are delivered to the device islet chamber via the inlet and outlet catheters and ports. The islets take up residence within the islet chamber of the device and are provided with essential nutrients and oxygen via mass transfer from across the immunoprotective membrane from the vascularized chamber of the device. For example, as blood glucose levels rise following a meal, the glucose levels rise rapidly within the vascularized region of the device and glucose diffuses across the immunoprotective membrane resulting in an increase in glucose levels within the islet chamber resulting in the release of insulin from the islets which diffuses back across the immunoprotective membrane being rapidly taken up by the extensive capillary network existing in the vascularized chamber and the insulin is then distributed throughout the body where its ultimate action is to regulate blood glucose levels. The level of glucose control achieved and the number of islets required

can be defined using the methods outlined in "A Comparison of Islet Transplantation and Subcutaneous Insulin Injections for the Treatment of Diabetes", *Computers in Biology and Medicine*, Volume 21, pp. 417-427, 1991, Brian Smith, Jeffrey G. Sarver, Ronald L. Fournier.

What is claimed is:

1. A bioartificial device for implantation into an animal comprising:

a housing having an enclosed chamber containing metabolically active cells,

at least one vascularizing compartment having an opening that provides access to surrounding tissue,

inlet means for supplying cells to the chamber,

outlet means for removing cells from the chamber, and

a semi-permeable membrane separating and in communication with the chamber and vascularizing compartment, the membrane providing immunoprotection of the active cells from the vascularizing compartment and around the implanted device, the membrane allowing passage of small molecules including nutrients and waste products between the chamber and vascularizing compartment and not allowing passage of agents of an immune system to the chamber, and

a biocompatible matrix in the vascularizing compartment to provide a neovascular formation region for enhancing growth of small capillaries for providing efficient mass transfer of substances between the chamber and the capillaries in the vascularizing compartment, the matrix having a porosity of about 40 to 95 percent and interconnecting passageways of about 10 to 120 microns.

2. An organ as defined in claim 1 in which the metabolically active cells are islets of Langerhans.

3. An organ as defined in claim 1 in which the porosity is about 80 to 85 percent.

4. An organ as defined in claim 1 wherein the vascularizing compartment contains at least one growth factor for promoting ingrowth of capillaries into the vascularizing compartment.

5. An organ as defined in claim 1 in which a layer of islets is formed adjacent the membrane, the layer having a thickness and having a diameter that is greater than its thickness.

6. An organ as defined in claim 1 wherein the metabolically active cells produce at least one substance of therapeutic benefit to the animal.

7. An organ as defined in claim 5 wherein the cells produce at least one of parathyroid hormone, dopamine, insulin, glucagon, calcitonin.

8. An organ as defined in claim 1 in which a disc-like layer of active cells is formed in the chamber adjacent the membrane, the layer having a thickness and a diameter, wherein the diameter of the layer is at least as great as the thickness of the layer.

9. An organ as defined in claim 1 wherein metabolically active cells metabolize at least one toxic substance that diffuses from capillaries contained in the vascularizing compartment into the chamber.

10. An organ as defined in claim 1 wherein metabolically active cells secrete insulin in response to glucose which has diffused from capillaries contained in the vascularizing compartment into the chamber.

11. An organ as defined in claim 10 wherein metabolically active cells also secrete at least one of somatostatin, pancreatic polypeptide and glucagon.

12. An organ as defined in claim 1 wherein the membrane has an average number molecular weight cut-off of less than 100,000.

13. An organ as defined in claim 1 wherein the metabolically active cells are genetically engineered.

14. A bioartificial device for implantation into an animal comprising:

a housing having an enclosed chamber containing metabolically active cells that produce at least one substance of therapeutic benefit to the animal,

at least one vascularizing compartment having an opening that provides access to surrounding tissue, the at least one vascularizing compartment containing at least one growth factor for promoting ingrowth of capillaries into the vascularizing compartment,

inlet means for supplying cells to the chamber, outlet means for removing cells from the chamber, and

a semi-permeable membrane separating and in communication with the chamber and vascularizing compartment, the membrane providing immunoprotection of the active cells from the vascularizing compartment and around the implanted device, the membrane allowing passage of small molecules including nutrients and waste products between the chamber and vascularizing compartment and not allowing passage of agents of an immune system to the chamber, and

a biocompatible matrix in the vascularizing compartment to provide a neovascular formation region for enhancing growth of small capillaries for providing efficient

mass transfer of substances between the chamber and the capillaries in the vascularizing compartment, the matrix having a porosity of about 40 to 95 percent and interconnecting passageways of about 10 to 120 microns.

15. An organ as defined in claim 14 in which the metabolically active cells are islets of Langerhans.

16. An organ as defined in claim 15 in which a layer of islets is formed adjacent the membrane, the layer having a thickness and having a diameter, wherein the diameter of the layer is at least as great as the thickness of the layer.

17. An organ as defined in claim 14 wherein the cells produce at least one of parathyroid hormone, dopamine, insulin, glucagon, calcitonin.

18. An organ as defined in claim 14 wherein metabolically active cells metabolize at least one toxic substance that diffuses from capillaries contained in the vascularizing compartment into the chamber.

19. An organ as defined in claim 14 wherein metabolically active cells secrete insulin in response to glucose which has diffused from capillaries contained in the vascularizing compartment into the chamber.

20. An organ as defined in claim 14 wherein metabolically active cells also secrete at least one of somatostatin, pancreatic polypeptide and glucagon.

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