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DESCRIPTION

"PROCESS OF SYNTHESIS OF ASYMMETRIC POLYURETHANE BASED
5 MEMBRANES WITH HEMOCOMPATIBILITY CHARACTERISTICS AND
MEMBRANES OBTAINED BY SAID PROCESS"

FIELD OF THE INVENTION

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The present invention in the area of chemical and
biomedical engineering it was developed at Instituto
Superior Tecnico and relates to hemocompatible asymmetric
polyurethane membranes to be used in extracorporeal blood
15 oxygenators and in extracorporeal medical equipments or
devices requiring the contact of blood with membranes.

BACKGROUND OF THE INVENTION

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Extracorporeal blood oxygenators are medical
equipments used in surgical operations like open heart
surgery where lungs cannot perform their usual gas exchange
function of adding oxygen to the blood and removing carbon
dioxide from the blood. In 1953 the Gibbon oxygenator was
25 used with clinical success (1). It consisted of an ensemble
of vertical mettalic screens where the blood circulated
adjacently in the downward direction. This ensemble was
inserted in a chamber that allowed oxygen to be transferred
to the blood and carbon dioxide to be removed from it (1).

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In the next two decades this simple equipment triggered numerous developments in two main directions:

- 5 1 - The bubble oxygenators - these involved the direct bubbling of oxygen through the blood with the diffusion of the oxygen from the bubbles into the bloodstream and in the opposite direction the diffusion of carbon dioxide from the blood into the
10 . bubbles.
- 15 2 - The membrane oxygenators - they incorporated a semipermeable membrane that was interposed between the bloodstream and the gas phase and therefore
allowing at a controlled rate the permeation of oxygen into the blood and the passage of carbon dioxide from the blood into the oxygen stream.

In the first ones, the subsequent separation of
20 bubbles and foams was necessary as they presented the risk of damaging the red blood cells. In association with this drawback their use was limited to surgeries involving short times of a few hours. Despite that the use of bubble oxygenators continued till 1980 when they were to a great
25 extent substituted by the membrane oxygenators.

These allowed the support of patients during longer surgery times. They are currently designated by the abbreviation "ECMO" (extracorporeal membrane oxygenator).

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Although the ECMO represented a great advancement in decreasing the risks of blood damage and allowing longer times of surgery support they were in the years 1980 still
5 associated to several problems:

- the fluxes of oxygen transfer where still lower than the bubble oxygenators;
- 10 - the costs where high;
- there were higher risks of failure due to leakages;
- they required higher blood volumes.

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These problems have successfully being solved, firstly with the integration of the membrane module with the reservoir of venous blood and then with the incorporation of the improvements made on the manufacture
20 of other extracorporeal equipments like the ones of hemodialysis where leakages where controlled, robustness improved and costs decreased.

However the challenges in the development of
25 membrane blood oxygenators are not only posed at the level of the membrane configurations of flat sheet and hollow fibers modules but mainly at the level of development of new membranes associating properties of hemocompatibility and higher oxygen permeation rates.

The hollow fiber modules of most of the ECMO in use are frequently made of microporous membranes due to the fact that they are characterized by high gas permeation rates.

However despite the fact that the pores of the microporous membranes are of sufficiently reduced sizes to avoid the passage of the blood components like the red blood cells or the platelets, they are prone to severe fouling caused by adsorption of plasma proteins that leads to the activation of the coagulation cascade, formation of trombin, platelet adhesion and formation of thrombi. This means therefore that these membranes do not have hemocompatibility. In very general terms a membrane that is hemocompatible does not introduce by contact with blood in circulation any alteration of the blood and particularly does not induce hemolysis, thrombogenicity and platelet adhesion through the activation of the coagulation cascade.

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In accordance with British patent GB 1595058 another problem associated with microporous membranes is the passage of water to the gas compartment and the dissolution of carbon dioxide and subsequent decrease of concentration gradients and of the gas permeation rates to values below the average value in the human lungs. The authors of the patent GB 1595058 use a pulsed flux to maintain higher mass transfer rates.

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One form to overcome these problems is through the coating of the membranes or through the use of composite membranes as described in patents US 4,622,206 and US 2002/002815611 respectively.

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The patent EP1043035A1 mentions another problem connected to microporous membranes which is related to the fact that along the operation time there is occurrence of the intrusion of plasma to the oxygen side and this renders the oxygenator inoperational. The author of this patent EP 1043035A1 refers that this problem can be minimized through the use of a coating that although does not cover some of the very small pores it delays the period of time that the intrusion of plasma can lead to the non-operation of the oxygenator.

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Janvier et al. (3) mention that in a membrane of vinyl chloride having local roughness areas of the order of 9 μm , the platellet adhesion was multiplied by a factor of 3 when compared to a membrane with a smooth external surface.

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Homogeneous dense membranes either in the form of flat sheets or hollow fibers, may play an important role in the improvement of hemocompatibility due to the fact that in contrast with the microporous membranes, they display a surface morphology that assures a smoother membrane/blood interface. However, the dense membranes usually present low gas permeation rates that can be lower than the

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physiological levels required and therefore to meet the necessary oxygenation rate, the membrane surface area of the oxygenator should be increased. And this larger blood/membrane interface may lead to higher risks of blood
5 damage.

Also, the developmemnt of non-thrombogenic polymers like the ones reported in the patents US 5,004,461 and US 4,521,564 can only be an asset in the
10 solution of these problems if they prove to have film-forming properties and enable the formation of membranes with adequate flux permeate rates and with surface morphologies that associate adequate properties of hemocompatibility.

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At present, the clinical use of extracorporeal membrane blood oxygenators and hemodialyzers is always associated to administration of heparin to the patient. This assures that the contact of blood with the membranes
20 and with the equipments does not trigger thrombogenic effects, platelet adhesion and activation of the coagulation cascade. Although there are also reports claiming the minimization of these effects through the additional coating with heparin of the membranes and of the
25 equipment surfaces, Janvier G. et al. (3) refers on the contrary, the occurrence of negative interactions with the systemic heparin.

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BRIEF DESCRIPTION OF THE DRAWING

Figure 1 shows a cross section of an Integral Asymmetric Membrane.

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DESCRIPTION OF THE INVENTION

The present invention relates to a novel membrane that combines adequate properties of gas permeation and hemocompatibility for use in extracorporeal blood oxygenators.

The membranes are designed to allow permeation rates of oxygen and carbon dioxide that meet the physiological requirements with adequate membrane surface areas.

The development of the new polymeric material is an asset on the innovative tailoring of the morphology of the membrane surface in contact with blood and of the asymmetric cross-sectional membrane structure.

This combination of diffusion material properties and membrane structures allow the association of the required gas permeation rates with properties of hemocompatibility in terms of being non-hemolytic, non-thrombogenic and not displaying platelet adhesion.

The material and structural characteristics of the membranes are the outcome of combining in an innovative

single step a catalytic reaction of homogeneous phase polymerization with the formation of a polymer solution with physico-chemical characteristics that allow through the optimization of the casting conditions, the fabrication
5 of integral asymmetric membrane structures (figure 1).

The traditional integral asymmetric membranes are associated to the Loeb-Sourirajan phase - inversion technique which essentially is a physical process of
10 deposition/casting of a polymeric solution.

In the present invention the chemical process of polymerization which is carried out in homogeneous phase is essential in the definition of the structure of the
15 polymer, the polymer/solvent system interactions and therefore in the final structure of the polymer solution that acts as a precursor of the structure of the casted membranes.

20 The polymerization reagents are two pre-polymers: one of them having three terminal functional groups of isocyanate and the other having two terminal hydroxyl groups. This last pre-polymer can be selected among glycols, lactones and carbohydrates and this plays a
25 crucial role in relation to the membranes hemocompatibility properties.

The reaction between the two pre-polymers yielding polyurethanes with two soft segments is carried

out in a homogeneous phase of a mixture of solvents that may influence the preferential migration to the surface of soft segments that improve hemocompatibility.

5 The solvents are selected not only in accordance with the pre-polymers compatibility but also in relation to the requirement of having very different boiling points and volatilities. This is crucial to control the evaporation rate of the more volatile solvent and determines:

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1) the thickness of the dense layer of the integral asymmetric membranes;

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2) the low surface roughness of the face of the dense layer that will be in contact with the blood in circulation.

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The point 1) makes possible the creation of the very thin dense layers of the integral asymmetric membranes that are responsible for the augmentation of the diffusive fluxes of the gases through the membranes. In fact, the fluxes can be increased by an order of magnitude when compared to the ones of a dense symmetric membrane.

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The point 2) relates to the external surface face of the dense layer that is characterized for being very smooth and not presenting roughness that could induce shear stresses to the blood in circulation.

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In summary, the membranes of the present invention are associated to a simple fabrication process that does not involve the activation either by irradiation or chemically of the surface in contact with blood, as it
5 is required in the grafting of anti-thrombogenic groups to render the membranes hemocompatible.

The present membranes associate to the hemocompatibility properties the compatibility of having
10 high permeation rates of O₂ and CO₂.

Thus, the first object of the invention is the process of synthesis of hemocompatible polymeric membranes, comprising the simultaneous synthesis of a new polyurethane
15 based polymer and a casting polymer solution precursor of asymmetric membranes in accordance with the following steps:

- a) catalytic reaction between two pre-polymers
20 dissolved in a mixture of two solvents with different volatilities;
- b) controlled evaporation of the above solution after its spreading in the form of a film;
- 25 c) extraction of the less volatile solvent by exchange with a non-solvent;

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d) extraction of the catalyst and the residual solvents by immersion of the film in water or aqueous solutions; and

5 e) drying.

In said process, preferably, the polyurethane based polymer is synthesized from a reaction between a pre-polymer with three terminal isocyanate (NCO) groups (PP NCO) and a pre-polymer with two terminal hydroxyl (OH) groups (PP OH) and with simultaneous formation of a casting solution.

Usually, the pre-polymer PP NCO has molecular weights in the range from 2800 to 4500 Dalton and the pre-polymer PP OH in the range from 400 to 2500 Dalton.

Said process comprises, normally, a reactive mixture of two solvents, a few (2 or 3) drops of catalyst and the two pre-polymers with a total concentration in the range from 30 to 45% (p/p). Generally, the two pre-polymers are in relative proportions from 85 PP NCO/ 15 PP OH to 95 PP NCO / 5 PP OH expressed as a weight percentage.

25 The preferred pre-polymer PP OH is selected from the chemical family of lactones, glycols and carbohydrates.

Normally, in the process of the invention, the

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mixture of the solvents - solvent less volatile / solvent more volatile - is in the ranges from 75% p/p / 25% p/p to 95% p/p / 5% p/p, respectively.

5 Preferably the duration of the reaction is of one to two hours in accordance with the composition of the reaction mixture.

10 The final polymeric solution is normally cast in the form of a film over a smooth surface, with the control of the evaporation time in the range from 30 s to 100 s.

15 Preferably, the solvent and the catalyst impregnating the membrane are extracted and exchanged by means of a bath of water or aqueous solutions at a temperature range from 20 to 25° C.

20 The membranes obtained according to the process of the invention are hemocompatible, non-hemolytic and non-thrombogenic membranes and permeable to oxygen and carbon dioxide.

25 It is a second object of the invention a polyurethane hemocompatible integral asymmetric membranes, which has an integral assymmetric structure that displays:

- a) a very thin dense layer with thickness ranging from 0.1 to 1 μm , with the external side of this dense

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polymer layer, which will be the one in contact with the blood, being very smooth;

- 5 b) subjacent porous layer with thickness of around 100 μm , the external side of this layer being the one in contact with the oxygen permeating through the membrane.

 Preferably, in said membranes, the external side
10 of the dense layer has average pore sizes below 1 nm (nanometer), avoiding protein adsorption and inhibiting the formation of thrombi.

 The permeation of oxygen and carbon dioxide
15 through the dense layer is generally associated to a diffusion mechanism.

 The layer subjacent to the dense layer has, usually, a porous structure that does not offer significant
20 resistance to gas permeation, namely oxygen and carbon dioxide permeation.

 These membranes have application in medical equipment, such as extracorporeal membrane blood
25 oxygenators and other equipment involving membrane/blood contact, and as immunoisolation barriers in cellular therapy and in other industries such as the pharmaceutical and food industries.

Example 1

A polymerization reaction is carried out in a reactional mixture composed of two pre-polymers, two
5 solvents and a few drops (2-3) of a catalyst - Stannous Octoate.

The percentage of the mixture of the two pre-polymers is 40% p/p and the one of the solvents is 60% p/p.
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The pre-polymers, poly(propylene oxide) and poly(caprolactone) diol are in the proportion of 90:10, respectively.

15 The mixture of solvents, dimethylformamide and diethyl ether are in the proportion of 55% p/p and 5% p/p, respectively.

20 The mixture of pre-polymers, solvents and catalyst is agitated and made homogeneous and the reaction is then carried out under an inert atmosphere of nitrogen for two hours.

Membrane Formation

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The polymeric solution above described is spread with a calibrated knife of 250 μm over a glass plate very well clean and fat-free. After an exposition to air during one minute the plate is immersed in water at room temperature
30 during 24 hours.

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The membranes formed are then detached from the glass plate and taken to a oven to dry.

5 The membranes are then tested to the permeation to gases and present permeabilities to O₂ of 17.6 barrer and to CO₂ of 183.2 barrer which are higher than the ones of dense membranes.

10 The standard test ASTM F-756 (4) for hemolysis determines for these membranes an index of hemolysis (HI) - HI<2- which means that these membranes are non-hemolytic.

15 The thrombosis test is carried out upon the method of Imai and Nose (5) and for times of contact of the membranes with blood of ten minutes there is no observation of formation of thrombi.

20 For times higher than 10 min the percentage of formation of thrombi is much lower than the one corresponding to the existing results till the moment.

Example 2

25 The description of example one was followed with the exception than now in the mixture of the solvents there is 45% p/p of dimethylformamide and 15% p/p of diethyl ether.

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The time of exposure to air is now of 30 seconds.

These membranes were tested to gas permeation and the permeabilities to O₂ and to CO₂ are respectively of
5 32.5 and 225.3 barrer.

The results of hemocompatibility are identical with no hemolysis and no thrombogenicity at 10 min.

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CLAIMS

1. Process of synthesis of hemocompatible
5 polymeric membranes characterized by the simultaneous
synthesis of a new polyurethane based polymer and a casting
polymer solution precursor of asymmetric membranes in
accordance with the following steps:

- 10 a) catalytic reaction between two pre-polymers
dissolved in a mixture of two solvents with
different volatilities;
- 15 b) controlled evaporation of the above solution after
its spreading in the form of a film;
- c) extraction of the less volatile solvent by exchange
with a non-solvent;
- 20 d) extraction of the catalyst and the residual
solvents by immersion of the film in water or
aqueous solutions; and
- e) drying.

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2. Process according to claim 1, characterized
in that the polyurethane based polymer is synthesized from
a reaction between a pre-polymer with three terminal
isocyanate (NCO) groups (PP NCO) and a pre-polymer with two

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terminal hydroxyl (OH) groups (PP OH) and with simultaneous formation of a casting solution.

3. Process according to claim 2, characterized
5 in that the pre-polymer PP NCO has molecular weights in the range from 2800 to 4500 Dalton and the pre-polymer PP OH in the range from 400 to 2500 Dalton.

4. Process according to anyone of the previous
10 claims, characterized by a reactive mixture of two solvents, a few (2 or 3) drops of catalyst and the two pre-polymers with a total concentration in the range from 30 to 45% (p/p).

15 5. Process according to claim 4, characterized in that the two pre-polymers are in relative proportions from 85 PP NCO/ 15 PP OH to 95 PP NCO / 5 PP OH expressed as a weight percentage.

20 6. Process according to anyone of the previous claims, characterized in that the pre-polymer PP OH is selected from the chemical family of lactones, glycols and carbohydrates.

25 7. Process according to anyone of the previous claims, characterized in that the mixture of the solvents - solvent less volatile / solvent more volatile - is in the ranges from 75% p/p / 25% p/p to 95% p/p / 5% p/p, respectively.

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8. Process according to anyone of the previous claims, characterized in that the duration of the reaction is of one to two hours in accordance with the composition of the reaction mixture.

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9. Process according to anyone of the previous claims, characterized in that the final polymeric solution is cast in the form of a film over a smooth surface, with the control of the evaporation time in the range from 30 s to 100 s.

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10. Process according to anyone of the previous claims, characterized in that the solvent and the catalyst impregnating the membrane are extracted and exchanged by means of a bath of water or aqueous solutions at a temperature range from 20 to 25° C.

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11. Process according to anyone of the previous claims, characterized by the production of the integral asymmetric membranes, which are hemocompatible, non-hemolytic and non-thrombogenic membranes and permeable to oxygen and carbon dioxide.

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12. Polyurethane hemocompatible integral asymmetric membranes, obtained in accordance with anyone of the previous claims, characterized by an integral asymmetric structure that displays:

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- a) a very thin dense layer with thickness ranging from 0.1 to 1 μm , with the external side of this dense polymer layer, which will be the one in contact with the blood, being very smooth;

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- b) subjacent porous layer with thickness of around 100 μm , the external side of this layer being the one in contact with the oxygen permeating through the membrane.

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13. Polyurethane hemocompatible integral asymmetric membranes according to claim 12, characterized in that the external side of the dense layer has average pore sizes below 1 nm (nanometer), avoiding protein adsorption and inhibiting the formation of thrombi.

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14. Polyurethane hemocompatible integral asymmetric membranes according to claims 12 and 13, characterized in that the permeation of oxygen and carbon dioxide through the dense layer is associated to a diffusion mechanism.

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15. Polyurethane hemocompatible integral asymmetric membranes according to claim 14, characterized in that the layer subjacent to the dense layer has a porous structure that does not offer significant resistance to gas permeation, namely oxygen and carbon dioxide permeation.

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16. Polyurethane hemocompatible integral
asymmetric membranes according to the previous claims,
characterized in that they have application in medical
equipment, such as extracorporeal membrane blood
5 oxygenators and other equipment involving membrane/blood
contact, and as immunoisolation barriers in cellular
therapy and in other industries such as the pharmaceutical
and food industries.