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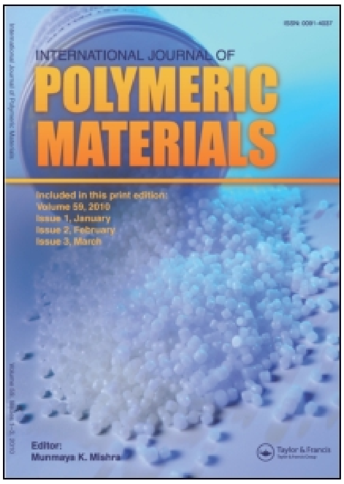

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Physico-Chemical Criteria for Estimating the Efficiency of Burn Dressings

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The medical treatments of burns usually involve the use of dressings. It is well known that frequently these treatments aggravate the injury. Since the methods for the estimating the burn dressing efficiency are very complex, their performance characteristics are usually not presented in the literature. We carried out a systematic study to develop a meaningful physico-chemical method of analysis to estimate burn dressing efficiency and establish criteria for their healing potential.

KEY WORDS Burns, medical treatments, dressings, treatment efficiency, methods of analysis.

INTRODUCTION

The principal medical treatment of burns is the use of dressings, which often worsen the effects of the injury.

It is difficult to estimate the effectiveness of the new burn dressings. Their physico-chemical properties are not usually presented in literature.

This is the first paper on this subject. The authors address the complexity of physico-chemical methods of analysis in order to create criteria for an efficienty dressings for a burnier wound surface.

1. Modern Surgical Burn Dressings

Dressings for wounds and burns must primarily be protective, surptional and atraumatic. In currently used dressings these properties are provided by a multilayered structure or structural modifications.

Different classifications of the dressings can be found in literature: by material, by construction or by functions.[1–3]

The dressings applied in the modern treatment of wounds and burns are subdivided into three groups according to material of the layer, sorbing the exudate of wounds; i.e., material of animal origin; synthetic, foamy polyurethane; material of vegetable origin.

1.1. Dressings based on materials of animal origin. Typical dressings for this group are collagen sponges, which are porous. Beside hydrophilic properties, collagen sponger provide higher sorption of liquid (in the range of 40–90 g/g).[1,4-9]

The patent literature describes in detail the methods of obtaining collagen dressings for wounds and burns. In the form of sponges and felt[10-13] based on materials of animal origin also include these made from biological artificial leathers based on liophilized goby's and swine cutis, produced as plates 0.5–0.7 mm thick. However these materials possess lower sorptional capacity than collagen dressings.

Dressings called "cultivated cutis" are also obtained from the epithelia of cells of the patient himself.[13]

The shortcoming of biological artificial leathers or biodressings their expense and their inability to retain, as a rule, their properties on storage.

1.2. Dressings based on synthetic materials. The demands inexpensive raw materials for the production of dressings for wounds and burns led to the production based on synthetic polymeric materials, particularly cellular polyurethane.[14-19]

Cellular urethanes, intended for medical puposes, are synthesized on the basis of toluilenediisocyanate and polyoxipropyleneglycole.[20]

The dressings based on polyurethanes have a pores distribution of about 200–300 pores/cm^2, and allow the regulation of the number and size of pores in layers.[21] On the whole, dressings from this group are prepared double layered, the outside layer being of higher density in order to prevent liquid evaporation and penetration of microorganisms. In rare case, these dressings are made homogeneous by all the thickness.

The influence of the pores sizes on sorptional properties of polyurethane sponges is described in the paper[22]: macroporous sponge with the pore size from 200 up to 2000 μm is completely nourished by exudate under pressure only. In this case through pores should possess the sizes of several micrometers.

Other polymeric materials (polyvinyl chlorade, nylon, etc.) are applied as the sorbing layer apart from polyurethanes.[23-26] This group should be added by compositional burn dressing, based on silicon film, polyamide network and hydrophilic admixture, produced by "Hall Woodroof" Company (USA).[13] Polyurethane covers with atraumatic lower layer from polyglycolic acid may be considered as variety of compositional dressings.[27] It is characteristic of dressings from this group, that they preserve their high strength properties at the absorption of the wounds exudate.

A two-component protective dressing "Hydron" was recently applied in the treatment of burns. It is a film, formed on the wound a powder of poly-2-hydro-oxiethylmetacrylate dissolves in polyethyleneglycol 400.[2,28] Although they possess good protective properties, "Hydron" dressings have low strength and sorptional capacity.

1.3. Dressings based on the materials of vegetable origin. A large number of burn dressings are so-called "cotton-batting" ones, based on cellulose, viscose or a combination of the two.[29-33] These dressings differ from each other by structure and composition of the upper and lower layers. Most often the sorptional layer from cellulose is used in complex dressings. Such dressings are usually layered, with the separate layers being produced from either the same material or from different ones, and may be a fixed mechanically or by using thermoplastic material. To decrease

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their adhesion to the wound surface, the lower layer is produced from various fabric and nonfabric materials (perforated Dacron, polypropylene, pressed paper, metallized fabric material, etc.). The total sorptional ability of these dressings is defined by hydrophilicity and porosity of the basic material and is usually equal 15–25 g/g.

Papers[1,34–35] show the dressing action data on wounds and burns of dressings based on another vegetable material—derivatives of alginic acid. Typical "Algipor" spec-

TABLE I

Characteristics of dressings in brief

No.	Name	Company	State	Structure	Composition
			Group 1		
1.	Collagen burn dressing	"Helitrex"	USA	Dressings uniform by thickness, dense, pores of 0.01 mm size. It has gauze cover.	Collagen
2.	Collagen sponge	"Helitrex"	USA	Similar to No. 1, differs by big radius of pores, formed by fibrill weaving of cylindric form preferably.	Collagen
3.	Collagen dressing	"Bayer"	Germany	Friable dressing, possesses rough porous structure with pores-holes sizes from 1.5 to 0.1 mm.	Collagen
4.	Burn curative dressing	"Combutec-K 11"	USA	Dressing of large-porous structure with pores size from 1 to 0.05 mm. Pores are of cylindric form preferably formed by fibrills weaving of collagen.	Collagen
5.	Biological dressing	"Corretium-2"	USA	Dense, pressed plate. Fibrillar structure is observed in dense layers.	Collagen
6.	Biological dressing	"Corretium-3"	USA	The same	Collagen
			Group 2		
7.	Compositional burn dressing	"Biobrant"	USA	Double-layered elastic, porous dressing, consists with the upper layer of 0.01–0.005 mm and flexible fabric nylon base. It represents combination of hydrophilic components with elastic silicon films.	Silicon, the main layer—from polyamide
8.	Synthetic dressing	"Epigard"	USA	Double-layered elastic porous dressing. Upper layer is dense, nonporous 0.2 mm thick.	The main layer—from polyurethane, upper one polypropylene
9.	Synthetic burn dressing	"Syncrite"	ChSSR	Single-layered dressing on gauze base with through large pores, medium flexible.	Polyurethane

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TABLE I (*Continued*)

No.	Name	Company	State	Structure	Composition
10.	Synthetic wound dressing	"Syspurderm"	GDR	Dressing of homogeneous composition, with different pore distribution: upper layer is 0.1 mm thick, possesses small porous structure with pores of 0.01 mm size; lower layer, adjoining wound possesses large pores of 0.05 mm size. Dressing is "elastic," accepts a form badly.	Polyurethane
11.	Synthetic wound dressing	"Farmexplant"	PBR	Antiseptic double-layered dressing. Main polyurethane layer possesses pores of 0.1–1.5 mm. Upper layer is 0.1 mm thick, more dense, nonporous.	Polyurethane
12.	Atraumatic caproic dressing		USSR	Large-cellular dressing on the basis of weaved nylon.	Polyamide
Group 3					
13.	Cover for wound, burns	VNIImed-polymer "Algipor"	USSR	Wound large-cellular dressing, homogeneous by its composition.	Alginic acid salts
14.	Needle-pierced fabric		USSR	Porous cotton balling dressing with atraumatic layer.	Cellulose
15.	Wound nonadhering dressing	"Bayersdorf"	Germany	Three-layered dressing of plaster type with tricot lower layer. Dressing is of sandwich type: upper layer-creped paper, main part is cotton balling, lower layer-tricot net. Atraumatic action is provided by effect of dressing "bending" (tunneling effect).	Main and upper layers—from cellulose, lower one is a film from Dacron or nylon
16.	Wound absorbing dressing	"Johnson-Johnson"	USA	Three-layered dressing with perforated lower and upper layers 0.01 mm thick, main part is cotton balling, porous.	Main layer—from cellulose, external layers—from polypropylene
17.	Haemostatic		Sweden	Double-layered dressing with perforated lower layer, sewed to the main layer.	Viscose main layer, atraumatic one —from polyethylene
18.	Wound dressing	"Mesorb"	France	Cotton balling or viscose dressing, creped paper—lower and upper layers.	Cellulose
19.	Surgical dressing	"Kendall"	USA	Similar to No. 16 with cellulose base and atraumatic synthetic lower layer.	Cellulose

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TABLE I (*Continued*)

No.	Name	Company	State	Structure	Composition
20.	Dressing with perforated metallized layer		Germany	First aid dressing with hydrofobic layer and lower metallized layer. Internal layers represent nonfabric pressed layer of creped paper.	Main layer—from cellulose, lower layer is aluminum spray coated.
21.	Dressing, lower layer is not metallized		Germany	Similar to No. 20.	Cellulose with spray-coated lower layer
22.	Nonadhesing dressing	"Switin"	ChSSR	Dense cotton balling dressing, lower and upper layers are nonfixed nylon networks.	Cellulose and polyamide
23.	Series of experimental dressings with various quantitative viscose-cotton composition		USSR	Cellulose or viscose dressings with atrauma-layer.	

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imens are used based on mixed sodium-calcium salt of alginic acid as spongy plates of about 10 mm thick with high absorption ability (Table I).

2. Selection of Properties of Burn Dressing Being Tested

The literature data showed that burn dressings, particularly the first aid ones, must perform three main functions[1-2,36-37]:

1. Absorb the wound exudate, which contains metabolism products and toxins.
2. Provide optimum water, air and heat exchange between the wound and the atmosphere.
3. Protect the wound from the penetration of microorganisms from the air.

Moreover, the burn dressing must be removable from the wound without further injury to the patient.

Therefore the following properties of burn dressings are studied to determine their efficiency.

2.1. Sorption-diffusional properties. Sorptional-diffusional properties of dressings are extremely important, because they determine the performance of the three main functions of dressings.

Water absorption: Water is the main component of exudate of wounds. At present, there is no opinion on how fast and in what degree the dressing must absorb the exudate enough to clean the wound from toxins and metabolism products while, the same time, keeping wound wet, enough to present the removal of water from healthy tissue.[1-2,36-37]

Air penetrability: Sufficient air must be allowed to penetrate the dressing since increased oxygen concentration helps the healing process.

Vapor penetrability: Vapor penetrability of skin of a healthy man is 0.5 $mg \cdot cm^{-2}$ $hour^{-1}$.[38] In absence of technical data it may be concluded that high vapor penetrability will lead to "drying" of dressing with a corresponding change of surface energy on the dressing-wound interface. On one hand this will promote undesirable removal of water from the tissues. On the other hand, it may cause the dressing to come off the wound. Low vapor penetrability of dressing will lead to the accumulation of liquid under the dressing, that may cause edema.

Penetrability with reference to microorganisms: Penetration of microorganisms through the dressing must be blocked to prevent infection.

2.2. Adhesive properties. The adhesive properties of dressings determine their ability to stay attached to the wound. Thus, the surface energy of the dressings siole facing the wound must always be lower than that of the wound surface.

2.3. Mechanical properties. The following two mechanical properties are important for dressings: flexural rigidity and strength at break.

The first defines the ability of the dressing to accept wound profile: the second is important since it allows the dressing to be removed from the wound completely without breaking.

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3. Methods of Investigation of Physico-Chemical Properties of Burn Dressings

3.1. Determination the materials porosity. The porosity of materials (the relation of pore space volume to total volume) is determined according to two methods:

1. Measuring density:

$$Q = 1 - \frac{\rho}{\rho_0}, \tag{3.1}$$

where Q = the material porosity; ρ = observable density; ρ_0 = density of the material, forming porous medium.

The value of ρ is determined by weighting of a sample with the known geometrical sizes. The value of ρ_0 is determined similarly for the samples, pressed under the pressure of 500 GPa.

2. From photos obtained by microscope we obtain

$$Q = \left[\frac{S_{\text{pores}}}{S_0}\right]^{3/2}, \tag{3.2}$$

where S_{pores} and S_0 = total surface of pores and general surface of the material in the field of vision of the microscope.

3.2. Determination of sizes and the amount of pores. The amount and sizes of pores are determined with the help of MIN-10 microscope in reflected light. The curve of pores distribution by radii is calculated.

3.3. Estimation of surface energy on the material-medium interface. Surface energy on the material-medium interface is estimated using the wetting angle of the material surface by the medium. A drop of liquid is applied to the surface of the material, and the angle is measured between the tangent at the base of the drop and

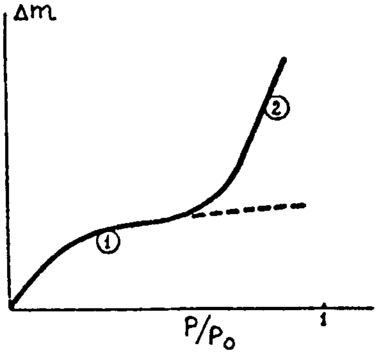

FIGURE 1 Sorption isotherm of low-molecular liquids by microporous materials: 1—real dissolving of liquid by the material; 2—condensation of liquid in the material microporous; m—sorbed liquid mass; P/P_0—relative pressure of liquid in thermostating vessel (P_0—pressure of saturated vapor of liquid in the present conditions).

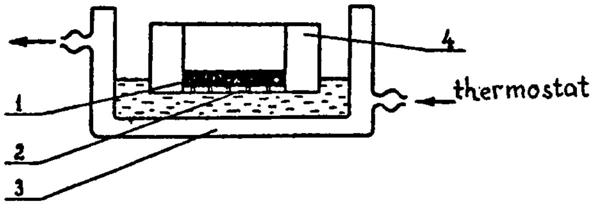

FIGURE 2 The scheme of device for determination of absorbing ability of the porous materials: 1—sample; 2—perforated plate; 3—thermostated camera; 4—float.

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the material surface. The wetting angle is determined using horizontal microscope HM. The accuracy of angle measurement does not exceed ±1°.

3.4. Determonation of sorptional ability of materials. The total amount of liquid sorbed by the material, includes the liquid in macropores with the size over 0.1 μm, in micropores with the size smaller than 0.1 μm and in the material matrix (dissolved liquid).

The amount of disolved liquid, and of liquid filling the micropores, is calculated from the dependence of the amount of sorbed liquid on pressure of vapors of that liquid over the sample (isotherms of sorption).

The sorption isoterms for the materials with micropores possess S-type forms (Figure 1). The first part of the curve is connected with the real desolving of liquid, the second one—with the condensation of liquid in micropores.

The maximal sorption (the amount of liquid, really solved and filling micro- and macropores) is determined with the help of the device, shown on the Figure 2. The device represents a vessel with liquid medium, in which a float of special perforated square construction is placed. The float construction is calculated to prevent its sinking. This requires that the liquid medium does not penetrate through the perforation of the square, but forming meniscus on the side of the square facing the porous interlayer. The change of the mass of porous material is determined from the immersion of the float with the sample. It is performed with the help of a horizontal microscope HM.

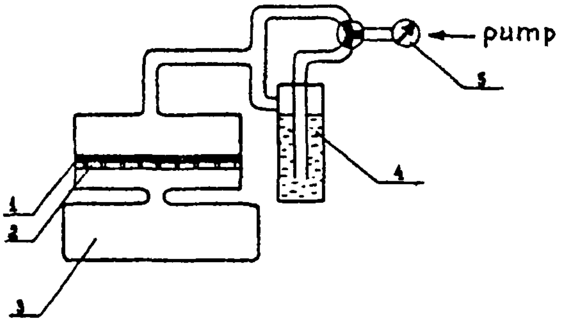

FIGURE 3 Device for determination of air penetrability of materials: 1—sample; 2—perforated plate; 3—polyethylene sack; 4—manometer; 5—pressure controller.

3.5. Determination of air penetrability of burn dressings. Air penetrability (the volume of the air, passed through the specific surface during the specific time) was determined with the help of device specially designed for this purpose. The device is a cylindric cell with perforated plate supporting the sample (Figure 3). The air was passed through the cell with the help of air compressor, equipped with manometer and pressure controller. We measured the time required to fill with air a polyethylene 45 l volume sack.

The sample of a round form was cut with the help of mould. Then the sample was placed on the perforated plate of the cell. The sample was pressed by screwing the air was compressed through the cell. The time of polyethylene sack filling was measured with the help of stop-watch. The method allows to determine the air penetrability of dry or wet materials.

3.6. Determination of adhesion of burn dressings. Adhesion of burn dressings was investigated on the device, representing the modification of the device, described in the paper.[39]

A 1 mm thick fiber glass plate, covered with three layers of medical gauze, was placed into the fiber glass cell having a working surface of 3 × 10 mm. The cell was filled with 5 ml of whole blood to which added by 1 ml of 2% solution of thrombine. The dressing tested was placed on the plate surface 1 min after. The cell with the sample was placed into thermostat at 37°C for 24 hours. The sample removal was performed at 90° angle with respect to the surface of the tested material.

3.7. Determination of vapor penetrability of burn dressings. Vapor penetrability (the mass of water, passed through the specific surface during the specific time) was determined with the help of the device, described in Reference 40. Glass vessel was filled with a definite amount of liquid, for example water or water solution of sulfuric acid. This amount provided the definite relative humidity. The investigated sample was placed on the vessel surface, metal ring was set and pressed to the vessel by special clamp. The vessel with the contents was weighted and placed into desiccator with dryer at 37°C. After definite period of time the vessel was taken out from the desiccator, weighted and then put back to the desiccator. The amount of water, passed through the sample, was determined by the mass losses of the vessel contents. The vessel of 40 mm diameter and 20 mm high was used in the experiments.

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TABLE II

Composition of edema liquid and blood plasma, g/ml

Components	Edema liquid	Blood plasma
Urea	$5.1 \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$
Sugar	$5.8 \cdot 10^{-6}$	$11.0 \cdot 10^{-6}$
Protein	$3.4 \cdot 10^{-2}$	$7.2 \cdot 10^{-2}$
Salts	$1.0 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
Albumine/Globuline	3.9	1.5

4. Experimental Results and Discussion

4.1. Determination of sorption ability of burn dressings. At applying the dressings on the burn wound there occurs first the wetting of the surface layer of the material and then sorption of the wound exudate into the dressing volume.

In this connection it is necessary to answer the following two questions:

1) What are the components of the exudate of wound and burns, being able to sorb by the material, and what is the way of sorption?

2) What is the maximum sorption of the separate components of the exudate by the dressing material?

The first question had not yet been addressed in the published literature. In regard to the second question, the maximum water sorption of different materials as follows was previously determined.[41] The sample was immersed into the water, dried fast by filter paper and then weighted. Such method did not allow one to measure the sorption kinetics, and its accuracy of the maximum sorption was low.

That is the reason why we have worked out the device for continuous measurement of sorption, which solved the above mentioned shortcomings (Chapter 3).

The exudate of the wounds contains water, salts, proteins, cells the damaged cells and various low- and high-molecular substances in relatively lower amounts. Table II shows the approximate composition of edema liquid in the burn wound. The composition of edema liquid changes in dependence on the burn degree: the worse the burn is, the higher the content of protein and the lower albumine to globuline ratio.[3] Similar data for the blood plasma are shown for comparison in the Table II.

Sorption of wounds exudate may proceed via filling of micro- and macropores, or dissolving in the material matrix.

Let consider sorption of different components of the wound exudate by the dressing material.

Water fills pores and dissolves in the material matrix. Water solubility is defined by the material hydrophilicity.

The solubility of water, salts and other low molecular substances in polymers is the subject to the following rules;

—solubility in hydrophilic polymers is defined by size and charge of low molecular substance;

—in hydrophobic polymers it is defined by vapor elasticity (the higher vapor elasticity is, the higher solubility is).[42]

Protein fill the pores of the size up to 10^{-2} m and may dissolve only in hydrogels of "Hydron" type with water content over 30% by mass.

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TABLE III

Solubility of water in various polymers

Polymer	Solubility, 10^2 g/g	*T*, K
Cellophane	40	303
Viscose fiber	46	303
Cotton	23	303
Cellulose diacetate	18	303
Cellulose triacetate	11.5	303
Polycaproamide	8.5	303
Polyethyleneterephtalate	0.3	303
Polydimethylsiloxane	0.07	308
Poly(2-oxiethyl-metacrylate)	40*	310
Polypropylene	0.007	298
Polytetraphluorethylene	0.01	293
Polyethylene (=0.923)	0.006	298
Polyurethane	1*	298
Polyvinylchloride	1.5	307

Note: * = measured by the authors.

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Cells fill only open pores of the size over 0.1–0.2 μm.

Solubility of water in polymers: As above mentioned modern burn dressings represent heterogeneous materials, usually consisting of several layers. The upper one having the air is, as a rule, more hydrophobic and less porous than the others.

Solubility of water in this layer will define its evaporation from the dressing surface and the heat exchange between the wound and the surrounding. The information about solubility of water in various polymers (Table III) are shown in the paper.[43]

Solubility of water was determined by the sorption method. Extreme values of sorption at the definite pressures of water vapors were calculated from the sorption curves, and then the sorption isotherms were constructed using the method described in the paper.[44]

Extreme values of sorption $\varphi_{H_2O}^{\infty}$ at the saturation pressure were determined by extrapolation of φ_{H_2O} to $P/P_s = 1$. The value $\varphi_{H_2O}^{\infty}$ equals to the solubility of water in polymer.

Maximum sorption ability of burn dressings: Modern burn dressings represent large-porous or fibrillar heterogeneous materials, possessing high free volume. At the contact with the wound the exudate will fill the free volume of the dressing, filling degree being defined by hydrophilicity of the material, the size and geometry of the free volume fraction.

Theoretical: Consider the filling process of the entire free volume of the material by liquid medium. The maximum sorption of the medium by the dressing will be calculated in the following way.

Mass of the medium, sorbed by the dressing material, m_c equals

$$m_c = V_\infty \rho_0 - V_0 \rho_0, \qquad (4.1)$$

where V_∞ and V_0 are volume of the dressing after and before sorption of the liquid medium, respectively; ρ_c and ρ_0 are the density of the liquid medium and the dressing material, respectively.

Maximum sorption of the liquid medium in this case is

$$C_c^\infty = \frac{m_c^\infty}{m_0} = \frac{V_\infty \rho_c}{V_0 \rho_0} - 1, \tag{4.2}$$

where m_0 = initial material mass.

Two particular cases are possible.

1. There is no swelling of the polymer during sorption, i.e. liquid medium fills the free volume space only. In this case $V_\infty = V_0$ and

$$C_c^\infty = \frac{\rho_c}{\rho_0} \tag{4.3}$$

2. For materials possessing low density, $\rho_0 < 0.1$ g/cm^3

$$C_c^\infty = \frac{\rho_c}{\rho_0} \tag{4.4}$$

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Maximal sorption of water by burn dressings: Sorption of water by burn dressings is measured using a device developed for this purpose by the authors (Chapter 3).

Experiments were performed in the following way. First, the weights of different mass were placed on the perforated plate of the device and the relative device immersing to the water was measured with the help of a horizontal microscope HM. Calibrating curve was represented in "weights masses—depth of device immersing" coordinates in the units of eyepiece of microscope. Angle coefficient equals 0.70 ± 0.02 g/unit.

Subsequently, the sample of a dressing was placed into the device, and the depth of the device immersing during time "h" was measured. The mass of the medium sorbed by the material was calculated from the correlation:

$$m_c = 0.70h \tag{4.5}$$

The extreme value of the sorbed medium mass was determined at $t \to \infty$. Maximal sorption of the medium by the material was calculated from Equations (4.3) and (4.4).

Table IV shows experimental and theoretical (calculated from (4.5)) values of $C_{H_2O}^\infty$ and values of ρ_0, determined experimentally and used for theoretical calculation.

Good correlation was observed between the experimental and theoretical values of $C_{H_2O}^\infty$ for the majority of dressings. This shows that practically the entire free volume is filled by liquid medium at the contact of dressings with water.

The exception is the "Algipore" dressing, the large pores of which become denser on filling with water entering because of collapse of the pore walls. In the end this leads to the decrease of the total volume of the dressing. Liquid medium may fill not the whole volume of dressings, if the material is sufficiently hydrophobic and poorly wetted with water.

TABLE IV

Experimental and theoretical data of maximum sorption of water by burn dressings

Covering name (material)	$C^{\infty}_{H_2O}$, g/g		ρ_0, g/cm^3
	Experimental	Theoretical	
Helitrex (collagen)	32 ± 2	33 ± 2	0.030 ± 0.007
Helitrex (collagen sponge)	58 ± 3	55 ± 3	0.018 ± 0.005
Collagen dressing	1.8 ± 0.1	2.8 ± 0.3	0.350 ± 0.07
Corretium-2 (collagen)	3.5 ± 0.3	3.3 ± 0.3	0.300 ± 0.07
Corretium-3 (collagen)	2.1 ± 0.2	3.0 ± 0.1	0.330 ± 0.05
Combutec-2 (collagen)	77.0 ± 5.0	66.0 ± 3.0	0.015 ± 0.005
Epigard (foamy polyurethane)	10.0 ± 0.3	15.0 ± 1.0	0.067 ± 0.005
Silicon-nylon composition	7.5 ± 0.2	7.7 ± 0.5	0.130 ± 0.03
Syspurderm (foamy polyurethane)	6.2 ± 0.2	7.1 ± 0.5	0.140 ± 0.03
Syncrite (foamy polyurethane)	20.0 ± 2.0	22.0 ± 1.5	0.050 ± 0.01
Farmexplant (foamy polyurethane)	12.0 ± 0.5	15.6 ± 3.0	0.064 ± 0.007
Johnson-Johnson (cellulose)	11.4 ± 0.5	10.0 ± 1.5	0.100 ± 0.03
Blood stopping (cellulose)	15.7 ± 0.9	12.5 ± 0.7	0.080 ± 0.006
Tunneling (cellulose)	4.3 ± 0.2	5.0 ± 0.4	0.200 ± 0.05
Switin (cellulose)	18.0 ± 2.0	20.0 ± 1.0	0.050 ± 0.005
Metallized (cellulose-paper)	12.4 ± 0.7	10.0 ± 0.5	0.100 ± 0.04
Needle-perforated (cellulose-viscose)	28.0 ± 2.5	30.0 ± 2.0	0.033 ± 0.007
Viscose 100%	25.0 ± 2.0	30.0 ± 2.0	0.033 ± 0.007
70% of cotton + 30% of viscose	31.0 ± 3.0	33.3 ± 3.0	0.030 ± 0.007
50% of cotton + 50% of viscose	25.0 ± 2.0	28.5 ± 2.0	0.035 ± 0.007
30% of cotton + 70% of viscose	28.0 ± 2.0	27.7 ± 2.0	0.036 ± 0.007
Algipore (vegetable)	30.0 ± 3.0	90.0 ± 5.0	0.011 ± 0.0002

TABLE V

Density, maximal water sorption, wetting angle and heat effect of sorption of water by different collagens

ρ_0, g/cm^3	$C^{\infty}_{H_2O}$, g/g		φ^0	ΔH, cal/g
	Experimental	Theoretical		
0.011	74	91	170	34.6
0.016	53	62.5	70	25.4
0.013	49	77	90	30.2
0.013	47	77	110	31.9
0.013	8	77	120	31.2
0.014	4	71.4	110	29.8
0.014	30	71.4	50	27.7

To test this assumption 7 collagen materials were investigated, which differed in the production method.

We investigated: density, maximal water sorption, wetting angle and heat effect of water sorption by the material. The latter was determined using the microcalorimeter LKB 2107 as follows. The sample of definite mass was exposed to vacuum in the Butch type cell, thermostated, and then the excess amount of water was introduced into the cell causing a forced filling of the material volume. The obtained results are presented in the Table V and on the Figure 4.

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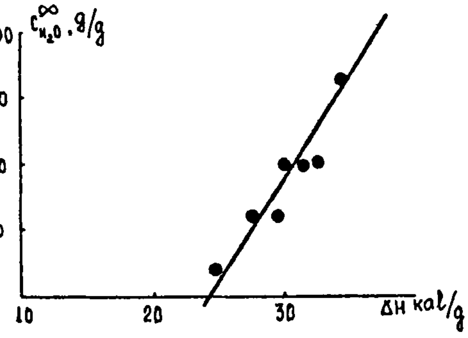

FIGURE 4 The dependence of maximum sorption of water by collagen materials on heat effect sorption.

The following conclusions can be made on the basis of the data presented in the Table V:

1. Experimental value of $C^{\infty}_{H_2O}$ is lower than "theoretical" one. This may be explained by two causes: the decrease of the total volume (as in the case of "Algipore") and nonfilling of a part of the material free volume by water.

2. A satisfactory correlation exists between the theoretical values of $C^{\infty}_{H_2O}$ and ΔH. Thus, the main cause of the difference between experimental and theoretical values of $C^{\infty}_{H_2O}$ is evidently in nonfilling of a part of the material free volume by water.

3. The absence of correlation between maximal water sorption and wetting angle, defined on the external surfaces of the material, shows that the values, obtained as mentioned above, do not reflect real interaction of water with internal surface of collagen.

Thus, it may be concluded that for the most number of burn dressings from hydrophilic materials, the maximum sorptional capacity with reference to water may be predicted satisfactorily. To fulfill this it is sufficient to use the Equation (4.4). For example, the experimental values of $C^{\infty}_{H_2O}$, correlate well with the free volume part of the materials (Figure 5). The correlation coefficient is 0.96.

Maximal sorption of plasma by burn dressings: Sorption of the blood plasma by burn dressings was determined by a similar method. Plasma was obtained by centrifugation of the conserved blood. The treatment of the experimental results was carried out similarly to the case of the investigation of maximal sorption of water. The value of $C^{\infty}_{\text{plasma}}$ differs from $C^{\infty}_{H_2O}$. The difference is not higher than 10%, that is why the data for $C^{\infty}_{\text{plasma}}$ are not shown in the Table V.

4.2. Study of the kinetics of the sorption of liquid media by burn dressings. The study of the kinetics of the sorption of the wound exudate by burn dressings is of great importance for the estimation of their efficiency.

The difficulties occurs at the mathematical description of the kinetics of the sorption process, connected with the absence of strictly quantitative description of the dressings structure.

Structure of burn dressings: Burn dressings are heterogeneous systems, consisting of several componet-phases. As the general attention in dressings must be paid to the material possessing the maximum penetrability with reference to liquid medium, it is necessary to classify the types of heterogeneous systems.

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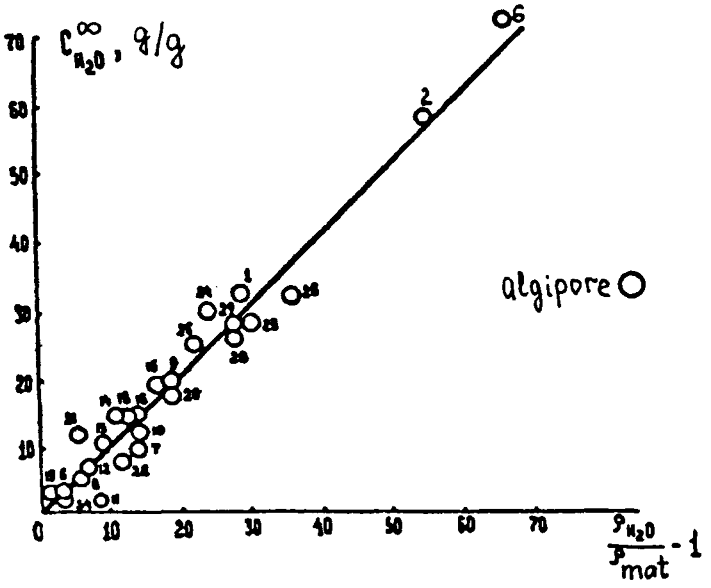

FIGURE 5 The dependence of C_{H_2O} on free volume of the material various burn dressings: 1—collagen dressing Helitrex; 2—collagen sponge Helitrex; 3—collagen dressing Braun; 4, 5—artificial leather Corretium 2 and 3; 6—Combutek-11; 7—synthetic dressing Epigard; 8—foamy polyurethane dressing Syspurderm; 9—synthetic dressing Syncrite; 10—foamy polyurethane dressing Farmexplant; 11—burn face mask; 12—compositional dressing Biobrant; 13—cellulose dressing Johnson-Johnson; 14—cellulose dressing Candall; 15—cellulose nonadhesive dressing Torcatee; 16—blood-stopping cellulose dressing; 17—cotton balling dressing Mesorb; 18—dressing with tunneling effect; 19—cellulose dressing with nonadhesive synthetic layer; 20—cotton balling dressing Svutyn; 21, 22—metallized dressings; 23, 24—needle perforated fabric with atraumatic layer; 25—viscose 100%; 26–29—viscose + cotton balling.

For example, the penetrable parts of the material are placed under the layer of another weakly penetrable material in the way that diffusing flow is directed perpendicularly to the surface layer. This is the case of double-layered dressings with a dense external layer. The penetrable parts of the material can be dispersed in a continuous weakly penetrable phase.

Dressings, based on collagen and cellulose, possess fibrillar structure and the fibers are randomly placed. In some cases spatial orientation of fibers is present. The sufficient amount of open pores in the dressings of such type is large but the open pores possess irregular form and great tortuosity in the direction of mass transfer.

Modern burn dressings are multilayered with more dense external layer.

Table VI shows the mean-radius of macropores and their amount per unit of square for dressings, based on polyurethane.

All dressings possess a mean-radius of macropores in the range of $2.0–3.0 \cdot 10^{-2}$ cm and a sufficiently narrow distribution (Figure 6).

Theoretical: The detailed analysis of a number of mathematical models and results of experimental investigations of heterogeneous systems was performed by Barrer.[45]

Dressings are of membrane form. If a membrane is in contact with the solution in a way that the concentration at one of its surfaces equals C_0 and at the other = 0

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TABLE VI

Mean-radius of macropores and their amount per unit of square N for dressings, based on polyurethane

Dressing name	R, cm $\cdot 10^{-2}$	N, pore/cm^2
Epigard	2.2 ± 0.2	370 ± 10
Syspurderm	1.8 ± 0.2	266 ± 5
Syncrite	2.8 ± 0.2	275 ± 5
Farmexplant	2.2 ± 0.2	300 ± 10

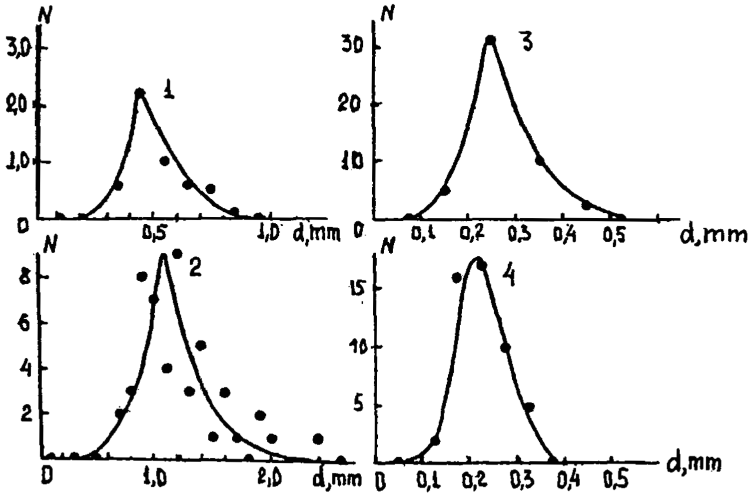

FIGURE 6 Curves of distribution of pores by sizes for different dressings: 1—Farmexplant; 2—Syncrite; 3—collagen dressing Braun; 4—Syspurderm.

at $t = 0$, then the total amount of the substance entered the membrane during time $t(m_t)$, is given by the equation:

$$\frac{m_\infty}{m_t} = 1 - \frac{8}{\pi^2} \exp\left[-\frac{D\pi^2 t}{l^2}\right], \tag{4.6}$$

where m_∞ = the amount of substance, entered the membrane at $t \rightarrow \infty$, i.e. in equilibrium; D = the coefficient of substance diffusion in the membrane; l = the membrane thickness.

The following correlation is satisfactory for the initial part of the kinetic curve of sorption:

$$\frac{m_t}{m_\infty} = 2\left[\frac{Dt}{\pi l^2}\right]^{1/2} \tag{4.7}$$

The Equation (4.6) was obtained for homogeneous material assuming that D does not depend on concentration of the substance in membrane. From the Equation (4.6) it is possible to calculate D value and time of membrane saturation by the substance

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up to a definite limit. For example, time of saturation up to $m_t/m_\infty = 0.85$ is calculated from the correlation:

$$\tau 0.85 = \frac{l^2}{6D}, \tag{4.8}$$

and $m_t/m_\infty = 0.97$ is reached during the time

$$\tau 0.97 = \frac{l^2}{3D}, \tag{4.9}$$

Both these correlations may be applied for practical calculations.

As it was mentioned above, the calculation of diffusion coefficient in heterogeneous systems is very difficult.

According to ideas accepted in the present time, the penetration of liquid into porous body is ruled by the laws of capillarity. These ideas are successfully applied for interpeting the penetration of water into paper, leather, fabrics, etc.[46]

Capillary pressure, which is the driving force of liquid to rise, is determined from Jurene equation[47]:

$$P_k = \frac{2\gamma_l \cos\theta}{r}, \tag{4.10}$$

where γ_l = surface tension of liquid; θ = wetting angle; r = capillary radius.

The equation, taking into account real structure of porous body, was obtained by Deriagin.[47]

Experimental: Kinetics of sorption of water and blood plasma was investigated using the device for the maximal sorption of water.

Figure 7 shows typical kinetic curves of sorption of water and plasma by various dressings. All curves are satisfactorily described by the Equation (4.7). Table VII shows the values of D_{eff}/l^2 and the value of $\tau_{0.85}$, calculated according to the Equation (4.8).

The following conclusions could be made from the Table VII data:

1. Burn dressings differ significantly in their rates of sorption of liquid media.
2. The rate of sorption is determined by the pores size and the material hydrophillicity.

4.3. Determination of vapor penetrability of burn dressings. With multilayered dressings, the external layer of is more dense than lower one which regulates the mass transfer of water from the wound into the surrounding. The process of mass transfer of water through the material layer is often called aquapenetrability or vapor penetrability.

Penetrability and diffusion of water in polymers were the subject of numerous investigations, the results of which are generalized in the list of reviews and monographs[43,49] and are presented in the Table VIII.

The mass transfer of water molecules in polymers possess a list of features. In

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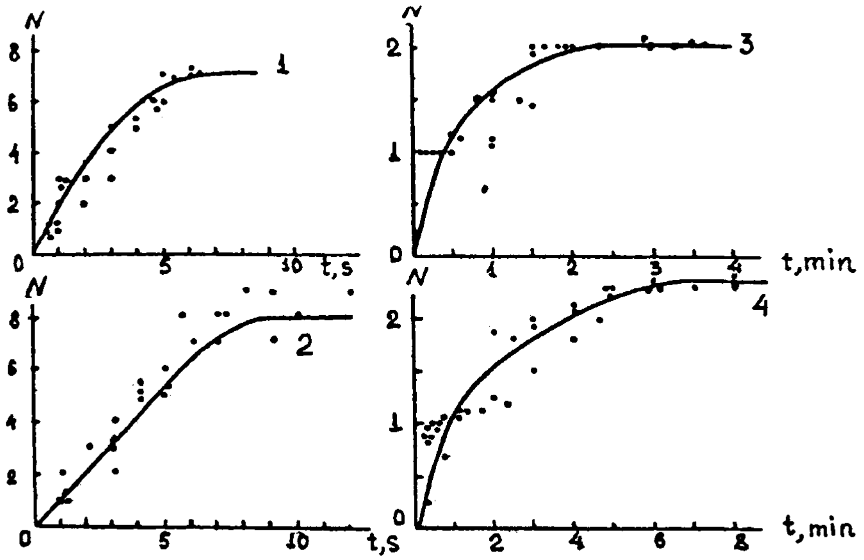

FIGURE 7 Curves of sorption of water and blood plasma by different burn dressings: 1—water—by needle perforated material; 2—plasma—by needle perforated material; 3—water—by polyurethane dressing Syspurderm; 4—plasma—by Syspurderm dressing.

TABLE VII

Values of D_{eff}/l^2 and $\tau_{0.85}$ for different burn dressings in water and plasma at 37°C

	$D_{eff}/l^2 \cdot 10^3$, s		$\tau_{0.85} \cdot 10^{-3}$, s	
Dressing name (material)	Water	Plasma	Water	Plasma
Helitrex (collagen)	2.5 ± 0.3	1.3 ± 0.2	3.9 ± 0.2	7.0 ± 0.3
Helitrex sponge (collagen)	6.6 ± 0.6	3.3 ± 0.4	1.5 ± 0.1	3.0 ± 0.15
Corretium-2 (collagen)	4.7 ± 0.4	2.5 ± 0.3	4.1 ± 0.2	8.0 ± 0.4
Combutek (collagen)	7.0 ± 0.7	3.5 ± 0.4	1.4 ± 0.1	3.0 ± 0.15
Syspurderm (foamy polyurethane)	2.3 ± 0.3	1.1 ± 0.1	4.3 ± 0.2	8.6 ± 0.4
Syncrite (foamy polyurethane)	(9.8 ± 0.8)*	(5.0 ± 0.5)	90 ± 10	200 ± 10
Switin (cellulose)	(4.5 ± 0.4)*	(2.2 ± 0.2)	210 ± 20	420 ± 35
Needle-perforated (cellulose)	35 ± 3	17 ± 1.7	0.3 ± 0.02	0.6 ± 0.05

*Must be multiplied by 10^{-2}.

hydrophilic matrices the interaction between water molecules and the material matrix is weak (low solubility). Nevertheless, the interaction of water molecules with each other stipulate a specific transfer mechanism.

In hydrophilic materials the interaction between water molecules and hydrophilic groups of the material matrix stipulates high solubility of water in the matrix and increased aquapenetrability.

Thus, high aquapenetrability may be the property of hydrophobic as well as of hydrophilic materials, however the causes will be different. For example, in hydrophilic polydimethylorganosiloxane the high mobility of water molecules is stipulated by high mobility of the chain units in this polymer. That is why despite low solu-

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TABLE VIII

Penetrability and diffusion of water vapors in polymers[49]

Polymer	T, K	p/p_0	$P \cdot 10^{15}$, mole · m/m^2 · s · Pa	$D \cdot 10^{12}$, m^2/s
Cellulose	298	1.0	8500	—
Regenerated cellulose	298	0.2	5700	0.1
Cellulose acetate	303	0.5–1.0	2000	1.7
Cellulose diacetate	298	1.0	15.7	—
Cellulose triacetate	298	1.0	5.5	—
Ethylcellulose	298	0.84	7950	18
Polydimethylorganosiloxane	308	0.2	14400	7000
Polyethylene (=0.922)	298	0–1.0	30	23
Polyethyleneterephtalate	298	0–1.0	58.6	0.39
Polypropylene	298	0–1.0	17	24
Polyvinyl chloride	303	—	—	2.3
Polycaproamide	298	0.5	134	0.097

bilities of water in polydimethylorganosiloxane the coefficient of aquapenetrability is significant.

On the opposite, in regenerated cellulose the diffusion coefficient is low because only the dissolved water molecules which are not connected with the matrix of this polymer participate in the mass transfer. In this case high value of aquapenetrability is stipulated by increasing the desolved water content in regenerative cellulose which increases the part of water molecules participating in the mass transfer. This in turn leads to the increase of both diffusion coefficient and penetrability coefficient.

Theoretical: The mass transfer of water through a porous body is practically equal to that of gases in a polymer, provided there is no interaction between water molecules and the matrix of polymeric material.

Since the hydrophilic materials are commonly used for the production of dressings, which actively interact with water molecules, the diffusion should be considered simultaneously with absorption.

As a rule, the rate of the absorption process is significantly higher than the diffusion rate. Therefore, it can be assumed that the absorption equilibrium is immediately reached. Therefore, the concentration of water in the material (C_{H_2O}) is obtained from the following equation:

$$\frac{\partial C_{H_2O}}{\partial t} = D_{H_2O} \frac{\partial^2 C_{H_2O}}{\partial x^2} - \frac{\partial C^a_{H_2O}}{\partial t}, \tag{4.11}$$

where D_{H_2O} = coefficient of water diffusion in the material; x = diffusion coordinate; $C^a_{H_2O}$ = concentration of the absorbed water.

The concentration of the absorbed water can be calculated for the particular cases. For example, if the concentration of functional groups, capable to link water molecules irreversibly, is limited and equals C_f, we can assume that the bonded water molecules no longer participate in the diffusion process, but form domains on which fast absorption occurs.

For the case, when the concentration of water on one of the surfaces ($x = 0$) is constant and equals $C^0_{H_2O}$, the reaction zone reaches the second surface of the membrane, which is l thick, during the time t.[50]

Thus, during the time t there will be no water flow through the surface $X = 1$ on the membrane exit, and then stationery flow will be set immediately. The amount of water passed through the membrane will equal

$$m_{H_2O} = D_{H_2O} \frac{\Delta C_{H_2O}}{l} \cdot S \cdot t, \tag{4.12}$$

where S = square of the membrane; $\Delta C_{H_2O}/l$ = gradient of the concentration.

If the solubility of water in the material is ruled by the Henry law:

$$C_{H_2O} = \sigma P, \tag{4.13}$$

where P = pressure of water vapors over the material, then we obtain the following equation, substituting (4.13) into (4.12):

$$m_{H_2O} = D_{H_2O} \cdot \sigma_{H_2O} \frac{\Delta P}{l} St, \tag{4.14}$$

Considering the diffusional coefficient P_{H_2O} being equal:

$$P_{H_2O} = D_{H_2O} \cdot \sigma_{H_2O}, \tag{4.15}$$

we obtain

$$P_{H_2O} = \frac{m_{H_2O} l}{\Delta P \cdot S \cdot t} \tag{4.16}$$

Experimental: Aquapenetrability of burn dressings was determined on the device, described in the Chapter 3. The values of penetrability coefficients were calculated from the Equation (4.16).

Table IX shows the values of coefficients of aquapenetrability P_{H_2O} for various burn dressings.

4.4 Determination of the air penetrability of burn dressing. As it was mentioned in 4.1 active sorption of the wound exudate occurs during several minutes after the burn wound is closed by dressing. Further on, there proceeds the evaporation of water from the external side of the dressing. This leads to the change of the state of exudate in the material mass. On the whole, this changes penetrability of the dressing with respect to air. In this case in order for anaerobic conditions not to be created in the wound, it is necessary to provide optimal air penetrability during the entire period of application.

The data on penetrability of dressings according to dry air are known in literature. Thus, for example, in Reference 51 it is recommended to determine air penetrability

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TABLE IX

Values of aquapenetrability coefficients of burn dressings at 37°C

Dressing name (material)	$P_{H_2O} \cdot 10^9$, mole·m/m²·s·Pa
Helitrex (collagen)	1.6 ± 0.1
Helitrex sponge (collagen)	11.0 ± 1.0
Brown dressing (collagen)	6.6 ± 0.6
Syspurderm (foamy polyurethane)	0.8 ± 0.2
Syncrite (foamy polyurethane)	1.2 ± 0.2
Epigard (foamy polyurethane)	4.3 ± 0.4
Farmexplant (foamy polyurethane)	3.3 ± 0.3
Biobrant (silicon-polyamide)	1.6 ± 0.16
Johnson-Johnson (cellulose)	2.0 ± 0.2
Perforated metallized dressing (cellulose)	9.0 ± 0.7
Face mask dressing (cellulose)	2.5 ± 0.2
Burn towel (cellulose)	5.4 ± 0.5
50% cotton + 50% viscose	8.0 ± 0.7
70% cotton + 30% viscose	8.0 ± 0.7
100% viscose	7.0 ± 0.7

TABLE X

Polymer	Penetrability coefficient (mole·m/m²·s·Pa)·10^{15}		Separation coefficient, $O_2 - N_2$
	O_2	N_2	
Polycaproamide	0.013	0.0033	3.8
Polyvinylchloride	0.022	0.008	2.8
Polyurethanic elastomer	0.032	0.10	3.2
Polyethylene (ρ = 0.940)	0.35	0.13	2.7
Polystyrene	3.13	0.73	2.9
Teflon	2.07	0.67	3.1
Ethylcellulose	3.2	0.93	3.4
Polydimethylsiloxane	168	83.0	2.0
Silicon rubber	200	87.0	2.3

with the help of industrially produced VPTM-2 device. This device records automatically the amount of the air, passed through the dressing of the known square during time t at pressure oscillations of about 5 mm H_2O. However the application of such device does not allow us to investigate the air penetrability of dense materials such as foamy polyurethane compositions, and most importantly of dressings in wet state.

The construction and principle of action of the device, developed by the authors, allowing the determination of air penetrability of any material in any states and conditions, were described in the Chapter 3.

***Penetrability of various materials according to oxygen and nitrogen*:** The coefficient of gas penetrability (as well as of vapor penetrability) is calculated according to the formula (4.16).

The literature data on penetrability or various polymers according to the oxygen and nitrogen are given in Table X.

As it is seen from the data presented in the Table X, the penetrability of polymers may differ by four orders of magnitude. Special attention should be paid to high gas

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TABLE XI

Values of penetrability coefficients P (mole·m/m^2·s·Pa), diffusion D (m^2/s) and solubility σ (mole/m^3·Pa) of gases into polydimethylsiloxane at 20°C[52]

Gases	$P \cdot 10^{15}$	$D \cdot 10^{10}$	$\sigma \cdot 10^{6}$
N_2	83	23.3	36
O_2	164	30	55.6
CO_2	720	—	—

penetrability of polydimethylsiloxane and compositions on its basis, which is the result of the increased solubility of gases in them at high rate of diffusion (Table XI).

Penetrability of porous materials, filled by liquid medium: A short list of studies considering the investigations of gas penetrability of polymeric membranes, in contact with a liquid is given in Reference 53.

It was observed, that the sorption of liquid by a polymer leads to a decrease of gas penetrability coefficient in comparison with the liquid free polymer.

Theoretical: Let us consider the mass transfer of the air through porous body in two cases: one in which the free volume of all pores is filled by the air and the other with free volume filled by liquid medium. Porous body may be presented as consisting of two phases: the material forming the body's carcass and free space.

We also assume that pores possess cubic form and are disposed in the volume of the body, not joining each other. Such model is sufficiently suitable for porous burn dressings.

Let determine the total thickness of the body in the direction of the mass transfer, total thickness of free space, occupied by pores, and total thickness of the layer, occupied by the material.

The total thickness of the body in the direction of the mass transfer is

$$l_\Sigma = \frac{V}{S}, \tag{4.17}$$

where V and S = volume and surface, respectively.

Total thickness of free space, occupied by pores, is

$$l_{\text{pores}} = l_\Sigma Q^{1/3} = \frac{V}{S} \cdot Q^{1/3} \tag{4.18}$$

where $Q_{\text{pores}} = V_{\text{pores}}/V$ = porosity.

The total thickness of the layer, occupied by the material, is

$$l_{\text{mat}} = l_\Sigma - l_{\text{pores}} = \frac{V}{S}(1 - Q^{1/3}). \tag{4.19}$$

Thus the air passing through the porous body will overcome the resistance of two layers, each possessing its own penetrability coefficient with respect to air.

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TABLE XII

Values of coefficients of penetrability, diffusion and solubility of the oxygen in air, water, plasma and blood at 37°C (dimensions as in the Table XI)

Medium	P	D	σ
Air	$2.5 \cdot 10^{-9}$	$2.7 \cdot 10^{-5}$	$9.4 \cdot 10^{-5}$
Water	$7.4 \cdot 10^{-14}$	$3.0 \cdot 10^{-9}$*	$2.5 \cdot 10^{-5}$*
Plasma	—	$2.0 \cdot 10^{-9}$*	—
Blood	$1.4 \cdot 10^{-14}$	$1.4 \cdot 10^{-9}$*	$1.0 \cdot 10^{-5}$*

*The values were taken from Reference 53.

Total penetrability coefficient P_Σ of the porous body equals

$$\frac{1}{P_\Sigma} = \frac{l_{\text{pores}}}{l_\Sigma P_{\text{pores}}} + \frac{l_{\text{mat}}}{l_\Sigma P_{\text{mat}}}, \tag{4.20}$$

where P_{pores} and P_{mat} = penetrability coefficients of the medium, presenting in pores; and the material, forming the body's carcass, respectively.

Let determine the ratio of penetrability coefficients of the porous body according to air, when its pores are filled by liquid and air.

$$\frac{P_{\Sigma(l)}}{P_{\Sigma(\text{air})}} = \frac{\dfrac{P_{\text{mat}}}{P_{\text{air}}} + 1}{\xi \dfrac{P_{\text{mat}}}{P_l}}, \tag{4.21}$$

where

$$\xi = \frac{Q^{1/3}}{1 - Q^{1/3}} \tag{4.22}$$

Values of P_{mat} are shown in the Table XII.

Values of P_{air} and P_l can be estimated from the coefficients of diffusion and solubility of oxygen in air, water, plasma and blood at 37°C.

Values of penetrability coefficients of the oxygen in various media may be calculated according to the following expression:

$$P = D \cdot \sigma. \tag{4.23}$$

For any material $P_{\text{air}} >> P_{\text{mat}}$, so we obtain more simple expression:

$$\frac{P_{\Sigma(\text{air})}}{P_\Sigma(l)} \approx \xi \frac{P_{\text{mat}}}{P_l} + 1 \tag{4.24}$$

As for the majority of dressings $\xi >> 1$, and P_{mat} and P_l are of the same degree,

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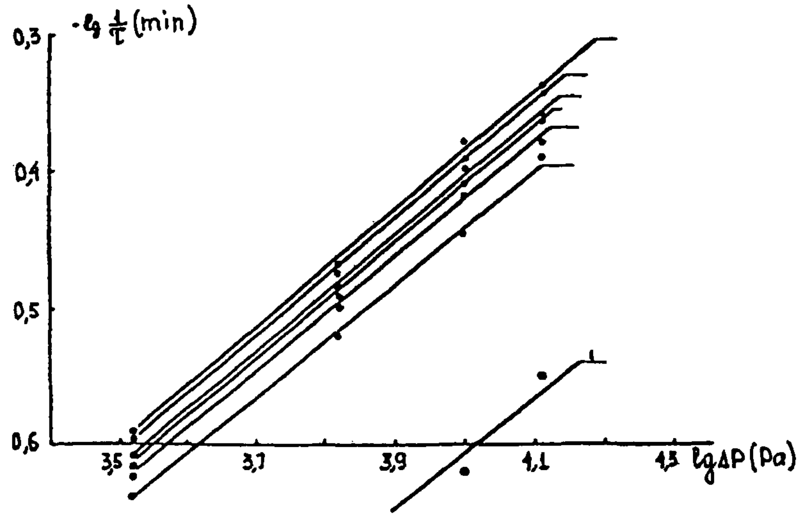

FIGURE 8 The dependence of 1/lg τ on pressure in the system for dry air: 1—needle perforated material; 2—collagen sponge; 3—Syspurderm; 4—Syncrite; 5—cellulose dressing Svutyn; 6—Farmexplant; 7—Epigard.

the decrease of air penetrability of the dressing at pores filling by liquid must be then significant.

Experimental: Air penetrability of burn dressings was determined using the device developed for this purpose (Chapter 4).

Two types of experiments were performed: determination of air penetrability for dry air and determination of air penetrability of dressings, preliminarily saturated by water (in conditions of maximal sorption of water), for humid air.

It has been shown by special experiment that air humidity (from 40 to 100%) does not practically influence the rate of penetration.

The experiments were performed according to the following scheme. At first we determined the time of filling by air of polyethylene sack of 45 l volume in conditions, when the sample was not in the cell. This time (the constant of the device) depended on pressure in the system (p):

$$\lg \frac{1}{t} = -2.00 + 0.44 \lg p. \tag{4.25}$$

The time of polyethylene sack filling at $p = 100$ Pa was selected as the standard. At $T = (21 \pm 1)$°C, $t_0 = 16.0 \pm 0.1$ min.

Subsequently the time of polyethylene sack filling with the sample was placed into the cell was similarly determined. It was observed (Figure 8), that the dependence of t_x on p is described with the same slope as in (4.25) for all investigated dressings in conditions of the dry air penetration:

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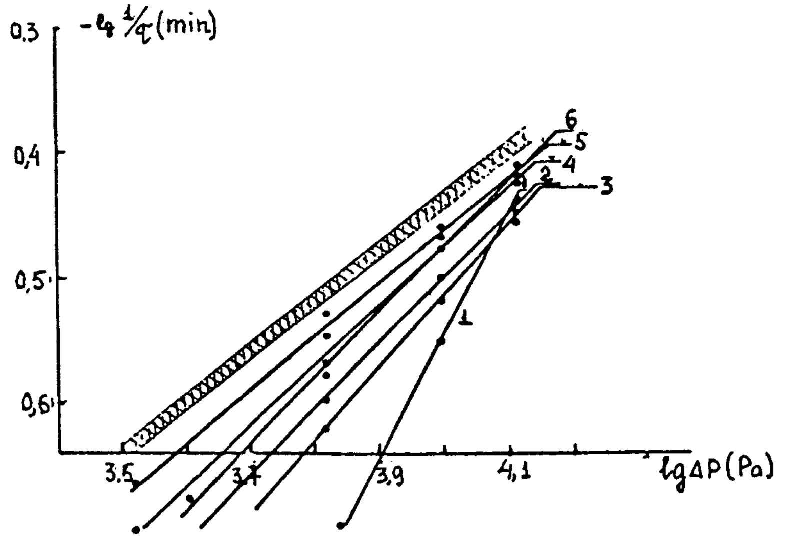

FIGURE 9 The dependence of 1/lg τ on pressure in the system for humid air: 1—needle perforated material; 2—Farmexplant; 3—Combutek; 4—Syspurderm; 5—compositional dressing Biobrant (silicon-polyamide); 6—Epigard.

$$\lg \frac{1}{t_x} = -A_x + 0.44 \lg p, \tag{4.26}$$

where A_x = constant, depending on structure and properties of the dressing material.

At bubbling humid air through the dressing saturated by water, the slope increased significantly. That is why it is necessary to perform several experiments for each dressing at different pressures in order to extrapolate t_x to the pressure of 100 Pa with the required accuracy (Figure 9).

The increase the slope of $\lg(1/t_x) - \lg p$ at air bubbling through the dressing saturated by water was attributed to the change of the material structure of the dressing resulting from the change of forms and sizes of macropores. This is often accompanied by a decrease of the total volume of the dressing.

Coefficient of air penetrability of the dressing (P_x) was calculated according to the equation:

$$P_x = \frac{ml_x}{S \cdot p \cdot (t_x - t_0)}, \tag{4.27}$$

where m = polyethylene sack bulk equal 2 moles of air at 21 ± 1°C; S = surface square, contacting with the bubbling air, equal $1.8 \cdot 10^{-3}$ m^2; p = 100 Pa.

Thus

$$P_x = 11 \frac{l_x}{(t_x - t_0)} \tag{4.28}$$

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TABLE XIII

Coefficients of air penetrability for dry and water saturated burn dressings at temperature of (21 ± 1)°C

Dressings (material)	Coefficient of air penetrability, mole · m/m^2 · s · Pa Dry	 Water saturated
Helitrex (collagen)	$2.7 \cdot 10^{-5}$	0
Combutek (collagen)	$1.1 \cdot 10^{-3}$	0
Epigard (foamy polyurethane)	$1.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$
Syspurderm (foamy polyurethane)	$1.3 \cdot 10^{-4}$	$1.0 \cdot 10^{-6}$
Symcrite (foamy polyurethane)	$1.1 \cdot 10^{-3}$	$4.0 \cdot 10^{-5}$
Farmexplant (foamy polyurethane)	$4.5 \cdot 10^{-5}$	0
Biobrant (polyamide + silicon)	$1.8 \cdot 10^{-4}$	$7.0 \cdot 10^{-5}$
Johnson-Johnson (cellulose)	$1.6 \cdot 10^{-4}$	$3.0 \cdot 10^{-6}$
Needle-perforated material (cellulose)	$1.1 \cdot 10^{-3}$	—

The value of air penetrability coefficients for the dressings dry and saturated by water are shown in the Table XIII.

From the data shown in this table we see that on saturation with water a significant decrease of air penetrability takes place for all dressings, except for the "Biobrant."

Penetrability coefficient for dry dressings can be calculated according to the following equation:

$$\frac{1}{P_{\Sigma(\text{air})}} = \frac{Q^{1/3}}{P_{\text{air}}} + \frac{(1 - Q^{1/3})}{P_{\text{mat}}} \tag{4.29}$$

P_{air} is obtained from the expression (4.23), using $D = 2.7 \cdot 10^{-5}$ m^2/s and = 45 mole/m^3 (solubility at atmosphere pressure). The value of P_{air} is $1.2 \cdot 10^{-3}$ mole · m/m^2 · s · Pa. The value of $P_{\Sigma(\text{air})}$ were taken from the Table XIII.

Values of P_{mat} were calculated from the Equation (4.24).

The values of $P_{\Sigma(H_2O)}$ can be obtained from the following equation:

$$\frac{1}{P_{\Sigma(H_2O)}} = \frac{Q^{1/3}}{P_{H_2O}} + \frac{(1 - Q^{1/3})}{P_{\text{mat}}}. \tag{4.30}$$

According to the calculations of $P_{\Sigma(H_2O)}$, its values fall close to 10^{-8} mole · m/m^2 · s · Pa for the majority of dressings. It is this result which reveals the extremely low air penetrability for the listed dressings.

For some dressings the value of $P_{\Sigma(H_2O)}$ is significantly higher than 10^{-8} mole · m/m^2 · s · Pa. This can be explained by two effects:

1. The presence of the air flow along the surface of pores (surface flow)[50];
2. The pressure of channels in the materials that are free of water.

To test these suppositions additional investigations are required.

4.5. Determination of adhesion of burn dressings. Adhesion properties play a key role in the dressing performance. On one hand the lower layer of the dressing

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must be easily wetted, providing good adhesion of the dressing to the wound. On the other hand, the surface energy on the dressing-wound interface must be minimal to provide the smallest trauma on its removal from the wound.

Theoretical: The adhesive strength characterizes the ability of an adhesive structure to preserve its integrity. The adhesive strength as well as the strength of homogeneous solids is of kinetic nature. That is why the rate of tension increase and temperature affect the adhesive strength and the scale factor (i.e. sample dimensions) are also of great importance.

Different theories of adhesion of polymers were previously suggested.[55]

1. Mechanical theory (MacBan), according to which the main role is devoted to mechanical filling of defects and pores of the surface (dressing) by the adhesive (blood).
2. Adsorptional theory (Mac-Loren), considering adhesion as a result of the performance of molecular interaction forces between contacting phases. According to this theory low adhesion, for example, may be reached between a substrate (dressing) with nonpolar groups and polar adhesive (blood).
3. Electrical theory (Deriagin), is based on the idea that the main factor controlling the strength of adhesive compounds rests in the double electrical layer which is formed on the adhesive-substrate interface.
4. Diffusional theory (Vojytzky), considers the adhesion as a result of interweaving of the polymers chains.
5. Molecular-kinetic theory (Lavrentiev), assumes that a continuous process of restoration and breakage of bonds proceeds in the zone of adhesive-substrate contact. Thus, the adhesive strength is defined by the difference between activation energies of the breakage and formation of bonds, and also depends on the correlation between the amount of segments participating in the formation of bonds and averge amount of molecular bonds per unit of the contact area.

In recent years, the thermodynamic concept receives the most attention. There, the main role is placed on the correlation of surface energies of adhesive and substrate.

Thermodynamic work of adhesion of a liquid to solid (W_a) is described by Dupret-Jung equation:

$$W_a = \gamma_l(1 \cos \theta), \tag{4.31}$$

where γ_l = surface tension of liquid; θ = wetting angle.

Substituting Jung's equation into (4.31)

$$\gamma_{s-l} = \gamma_s - \gamma_{s-l} \cos \theta, \tag{4.32}$$

we obtain the correlation

$$W_a = \gamma_s + \gamma_l - \gamma_{s-l} \tag{4.33}$$

where γ_s and γ_{s-l} = surface tension of solid and on the solid-liquid interface, respectively.

It follows from the Equation (4.33), that the higher W_a is the larger are the values

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TABLE XIV

Values of the surface tension and thermodynamic work of adhesion of various materials[28]

Material	γ_s, mN/m	W_{s-H_2O}, mN/m
Polytetrafluorethylene	18.5	83
Silicon rubber	21.0	78
Polyethylene	31.0	99
Polystyrene	33.0	105
Polymethylmetacrylate	39.0	103
Polychlorvinyl	39.0	101
Polyethyleneteraphtalate	43.0	104
Polycaproamide	46.0	107
Glass	170.0	222

TABLE XV

Adhesive strength (*a*) and the angle of wetting by water (θ) of various burn dressings

Dressing name (material)	*A*, N/m	θ^0
Corretium (collagen)	220 ± 20	75 ± 2
Syspurderm (foamy polyurethane)	210 ± 20	—
Epigard (foamy polyurethane)	350 ± 50	125 ± 3
Farmexplant (foamy polyurethane)	200 ± 20	130 ± 2
Bern-pack (cellulose)	170 ± 20	—
Biobrent (silicon-polyamide)	70 ± 10	—
Johnson-Johnson (cellulose)	20	—
Blood stopping nonadhesive dressing (cellulose)	20	—
Dressing with metallized lower layer (cellulose)	170 ± 50	—

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of γ_s and γ_l while γ_{s-l} are smaller. However, according to (4.33) the increase of γ_s must on one hand lead to the growth of W_a, and, on the other hand, to an increase of γ_{s-l}. That is why the increase of surface tension of the substrate is accompanied by the action of two effects. The necessary condition of the adhesive strength is $\gamma_l >> \gamma_s$.

Values of γ_l and W_{s-H_2O} for different materials are shown in the Table XIV.

The value of γ_l for blood equals 55.0.[56]

Experimental: Adhesive strength of burn dressings was determined according to the method, described in the Chapter 3. Table XV shows adhesive strength of various burn dressings and the angle of wetting by water also.

5. The Model of a Burn Dressing Action

Three main processes proceed at the application of a dressing to the wound:

1. Sorption of the wound exudate by dressing.
2. Water evaporation from the dressing surface.
3. Mass transfer of gases through the dressing in conditions of the proceeding of sorption and evaporation processes.

Processes 1 and 3 were analyzed in detail in the Chapter 4. It was found that sorption of the liquid media (water, plasma) proceeds fast and reaches the limiting value (maximal sorption ability) after several minutes for the most number of dressings, i.e. during the time sufficiently lower than that of the dressing action (2–3 days).

The mass transfer of gases (oxygen and nitrogen) through the dressing, is 2–4 orders of magnitude slower with wet samples, than with the dry ones in similar conditions.

Next, we consider the water evaporation from the dressing surface.

5.1. Evaporation of water from dressing surface. The dressing is saturated with water in air at 20°C temperature and 50% humidity. The temperature of the dressing surface is 32°C. This condition is chosen to take into account the temperature gradient in the matrix of the dressing.

Let us determine the amount of water, evaporating from the surface of the dressing during a given time period under stationery air, atmospheric pressure, and the dressing surface = completely saturated by water.

The partial pressure of air at 20°C and 50% relative humidity equals:

$$P_{H_2O} = 1.26 \cdot 10^{-3}\ \text{kg/cm}^2,$$

$$P_{air} = 1.02\ \text{kg/cm}^2.$$

For air at 32°C in the saturation state:

$$P_{H_2O} = 4.85 \cdot 10^{-2}\ \text{kg/cm}^2,$$

$$P_{air} = 0.98\ \text{kg/cm}^2$$

The values for density, viscosity, heat conductivity and heat capacity of air at average temperature of 26°C equal:

$$\rho = 1.185\ \text{kg/m}^3;$$

$$\mu = 1.861 \cdot 10^{-6}\ \text{g/m} \cdot \text{s};$$

$$\lambda = 6.1 \cdot 10^{-6}\ \text{kcal/m} \cdot \text{s} \cdot \text{grad};$$

$$C_p = 0.24\ \text{kcal/k} \cdot \text{grad}.$$

Using the method described in Reference 57, we can obtain after mathematical transformations the following equation for the mass transfer of water in dressing:

$$W = a_m \frac{P}{R \cdot T \cdot \rho_{av}} \cdot (p_1 - p_2), \tag{5.1}$$

where a_m = coefficient of heat conductivity; ρ_{av} = average value of the mixture density over the surface and near the surface of the dressings; p_1 and p_2 = partial pressure p_{H_2O} at 37°C and 20°C, respectively; R = the universal gas constant; P = atmospheric pressure.

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Substituting numerical values for the dressing of 1 × 1 m size, we obtain:

$$W = 1.2 \cdot 10^{-1}\ \mathrm{g/m^2 \cdot s}.$$

If the dressing surface is not completely occupied by water, we should apply the following correlation:

$$w = \frac{C_{\mathrm{surf(H_2O)}}}{C^0_{\mathrm{surf(H_2O)}}} \cdot 1.2 \cdot 10^{-1}\ \mathrm{g/m^2 \cdot s}, \tag{5.2}$$

where $C_{\mathrm{surf(H_2O)}}$ and $C^0_{\mathrm{surf(H_2O)}}$ = surface concentration of water on the external side of the dressing and free water surface, respectively.

5.2 Sorption of fluids by burn dressing from bulk containing a definite amount of fluid. Let us consider the case, where the burn dressing is applied to a wound, containing a definite amount of liquid. Assume that the dressing of a membrane of a given size (thickness and surface area S) is in contact with the solution of the restricted bulk V, which contains a $C_{0(s-s)}$ concentration of diffusive substance. As the dressing is saturated by this substance, the concentration of the latter in the bulk will decrease.

The solution of the diffusional equation has the following form[57]:

$$\frac{m}{m_\infty} = 1 - \frac{2a(1-a)}{1 + a + a^2q^2} \exp\left[\frac{4Dq^2t}{l_2}\right] \tag{5.3}$$

where q = positive solution of the characteristic equation

$$\mathrm{tg}\, q = -aq. \quad a = \frac{V}{\sigma S l},$$

where σ = the coeffficient of distribution of the substance between the membrane and the solution.

When a sufficient part of the substance in solution is sorbed by the membrane, the value of "a" is small and a more simple expression can be used:

$$m_t \approx m^\infty \left[1 - \frac{a}{(4\pi Dt/l^2)^{1/2}}\right] \tag{5.4}$$

From (5.3) and (5.4) we obtain two important correlations.

Sorptional ability of the dressing, i.e. the part of the substance sorbed from the solution in the equilibrium conditions, equals:

$$\frac{m_\infty}{m^0} = \frac{1}{1+a}. \tag{5.5}$$

Thus, for the efficient action of the dressing it is necessary that the concentration

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C to be as high as possible in relation to the products of metabolism and toxins. Relating to water $C_{H_2O} \sim 1$, it is desirable the dressing volume ($l\cdot S$) to be close to that of the exudate of wounds V.

The time of reaching 0.85 degree of maximum sorption of liquid media by the dressing equals:

$$\tau_{0.85} = 12\,\frac{a^2\cdot l^2}{\pi D} = 12\,\frac{V^2}{\pi D\sigma^2 S^2} \qquad (5.6)$$

It depends on many parameters, each being able to affect in order the time of completion of the sorption process.

5.3. Mass transfer of water from wound into the surrounding. Generally the change of the water amount under the dressing in the wound (m_{H_2O}) is determined from the correlation derived from the Equations (5.2) and (5.4):

$$m_{(H_2O)} = V\cdot C^0_{H_2O} - m^{\infty}_{H_2O(\mathrm{dressing})}\left[1 - \frac{a}{(4\pi Dt/l^2)^{1/2}}\right] - \frac{C_{\mathrm{surf}(H_2O)}}{C^0_{\mathrm{surf}(H_2O)}}\cdot 1.2\cdot 10^{-1}\cdot S\cdot t. \qquad (5.7)$$

Let consider the application of the correlation (5.7) for the following case. The wound characteristics are:

$$S = 10^{-2}\ \mathrm{m}^2,$$

$$C^0_{H_2O} = 10^6\ \mathrm{g/m^3},\ m^0_{H_2O} = 50\ \mathrm{g},\ V = 5.10^{-5}\ \mathrm{m}^3,$$

$$S = 10^{-2}\ \mathrm{m}^2,\ l = 10^{-3}\ \mathrm{m},\ \sigma_{H_2O} = 1,$$

$$D_{H_2O} = 10^{-9}\ \mathrm{m^2/s},$$

$$\frac{C_{\mathrm{surf}(H_2O)}}{C^0_{\mathrm{surf}(H_2O)}} = 0.5.$$

For these conditions

$$\tau 0.85 = 12\,\frac{25.10^{-10}}{\pi\cdot 10^{-9}\cdot 10^{-4}} = 9.5\cdot 10^2\ \mathrm{s}\ (\text{or} \sim 15\ \text{min})$$

$$\frac{m^{\infty}}{m^0} = \frac{1}{1 + \dfrac{5.10^{-5}}{10^{-2}\cdot 10^{-3}}} = 0.17\ \text{or}\ 8.5\ \mathrm{g}.$$

During the same time the following amount of water will evaporate *from the* dressing surface:

$$m_{\mathrm{evap}(H_2O)} < 0.5\cdot 1.2\cdot 10^{-1}\cdot 950\cdot 10^{-2} = 0.6\ \mathrm{g}.$$

i.e. the rate of evaporation is significantly (14 times) lower than that of water sorption by the dressing. All the amount of water from the wound (wound exudate) will evaporate during the time:

$$t = \frac{50}{0.5 \cdot 1.2 \cdot 10^{-1} \cdot 10^{-2}} = 8.3 \cdot 10^{4} \text{ s or} \sim 23 \text{ hours.}$$

6. Criteria of Efficiency of the First Aid Burn Dressings

6.1. The requirements of the first aid dressings. The first aid burn dressing must meet the following criteria:

1. Sorption of the wound exudate, containing products of metabolism and toxic substances, during the period of the dressing action (24–48 hours).
2. Wound isolation from infection of the external medium.
3. Optimum air and water transfer between the wound and the surrounding.
4. Easy removal from the wound, causing no damage to the wound surface.

6.2. Characteristics of burn dressings. Below we list the characteristics of the burn wounds on the basis of approximate estimations, discussed above. Note that no quantitative data are reported in the literature.

6.3. Rational criteria for the efficiency of the first aid burn dressings.

Sorptional ability of dressings: The burn wound (II–III degree) releases on the average 5.10^3 g/m^2 of exudate. As it is seen from the Table III, the water amount is about 90%. The sorption of different components of the exudate proceeds with different rates. In this case, the free volume of the dressing material will be first filled with water. The diffusion of proteins and cells takes place in space occupied by water.

Modern burn dressings possess porosity of 0.9 (Table IV) and almost the entire free volume can be filled with water (Fig. 5). Maximum sorption ability for such dressings equals

$$C_{H_2O} \approx \frac{\rho_{H_2O}}{\rho},$$

and the amount of the liquid sorbed per square unit is:

$$m_p \approx C^{\infty}_{H_2O} \cdot \rho \cdot l = \frac{\rho_{H_2O}}{\rho} \cdot \rho \cdot l \approx 10^6 \cdot l \text{ g/m}^2, \tag{6.1}$$

because $\rho_{H_2O} = 10^6$ g/m^3.

As the burn dressing of the first aid must sorb 5.10^3 g/m^2, it follows that

$$5.10^3 \approx 10^6 \cdot l \tag{6.2}$$

Therefore the thickness of the first aid burn dressing equals

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TABLE XVI

Characteristics of burn wounds[3]

Burn degree	Image of damage	Physiological process	Burn depth, mm
I	Redness and edema (medium edema)	Aseptic inflammatory process	0
II	Sac formation	Aseptic inflammatory process	0
III	Damage of skin cover, exudating wound surface	Skin necrosis, tissue necrosis	1–2
IV	Exudating wound surface	Full necrosis of tissues, carbonisation of tissues	2–5

TABLE XVII

Water losses by means of evaporation from burnt surfaces of different types

Surface type	Evaporation, $ml/cm^2 \cdot hour$
Natural skin	1–2
I-st degree of burn	1–2.5
II-nd degree of burn with intacts of sac	2.8
II-nd degree with no damage of hermentative layer	37
II–IV degree of burn	20–31

$$l \approx \frac{5.10^3}{10^6} \approx 5.10^{-3} \text{ m (0.5 cm)}$$

Thus, the first criterion of the efficiency of the first aid burn dressing can be formulated as follows:

The burn dressing of the first aid must use its entire free volume for sorption. This volume must be 0.9 or more of the total volume of dressing. Dressing thickness must be 0.5 cm or more.

It should be mentioned that the majority of foreign first aid dressings fulfill this criterion.

Air penetrability of dressings: The air penetrability of dry air of the most of dressings is in the range of 10^{-4}–10^{-5} $mole \cdot m/m^2 \cdot s \cdot Pa$ (Table XIII). The air penetrability of dressings filled with water is much lower and decreases to values between 10^{-6}–10^{-5} $mole \cdot m/m^2 \cdot s \cdot Pa$, that is 0.2–2 $dm^3/m^2 \cdot s$.†

Thus, the second criterion of the efficiency of the first aid burn dressings can be formulated as follows:

The first aid burn dressing must possess air penetrability of 10^{-5} $mole \cdot m/m^2 \cdot s \cdot Pa$ or higher after the sorption of water. For example, Biobrant burn dressing fulfills this criterion.

Adhesion of dressing to wound: Adhesion strength of dressings with respect to coagulated blood (Table XVI) varies in a wide range, but it has the minimum value of ~20 N/m. This value should be accepted as the optimal one, because it corresponds to the minimal pain and damage on removal from the surface of natural skin. Thus,

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†This is for the dressing 5.10^{-3} m (0.5 cm) thick at pressure of 50 Pa (5 mm H_2O) according to GOST 12088-77 (Standazts former USSR).

the third criterion of efficiency of the first aid burn dressings can be formulated as follows:

The first aid burn dressing must possess adhesive strength to the wound of 20 N/m or less after the end of its action.

The following burn dressings fulfill this criterion, for example: Biobrant, blood-stopping remedy, Johnson-Johnson.

Isolation of wound from infection from external medium: It is known, that microorganisms, causing the wound infection, do not penetrate through the filters, possessing average pores size ~0.5 μm. The fourth criterion of efficiency of the first aid burn dressings is then as follows:

The first air burn dressings must possess no open pores with average diameter larger than 5.10^{-7} m (0.5 μm).

Moreover, it is implied, that the first aid burn dressings possess sufficient mechanical strength and elasticity both in dry and humid conditions.

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CONCLUSION

The experimental methods to estimate the main physico-chemical properties were worked out.

Based on theoretical and experimental data we found that maximal sorptional ability of burn dressing equals the free volume of the dressing material, calculated from the value of the material density.

We found that to study sorption ability water can be used as a model liquid instead of blood plasma medium.

Kinetic parameters were determined from the sorption curves. These parameters showed that the first aid burn dressings markedly differ in the value of the rate or liquid media sorption at stages close to the sorption limits.

We established that the air penetrability parameter in wet state decreases abruptly by 2–3 orders of magnitude for the majority of tested dressings. This is due to the filling of porous space by liquid medium.

We recommended that the air penetrability parameter be determined in wet state which represents the common condition of action for the first air burn dressing.

The value of adhesive strength after the end of its action on the wound must not exceed 20 N/m.

From the data obtained in this study we formulated the following criteria to estimate the efficiency of the fist aid burn dressing: maximum sorptional ability for water must be at least 10 g/g; optimal thickness of dressings, fulfilling this value of sorptional capacity, must be $\sim 5.10^{-3}$ m, the adhesive strength must not exceed 20 N/min, and the average diameter of open (connected) pores must not exceed 5.10^{-7} m.

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