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Modification of Porous Carbon Sorbent with Tributyrin

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Abstract

Based on the results of adsorption studies, a procedure for modifying the porous carbon sorbent with tributyrin has been developed. The synthesis of tributyrin and the procedure of its quantitative determination in ethanol solutions by means of spectrophotometry are described. Carbon sorbent samples modified with tributyrin were obtained. Their properties have been studied using a complex of physicochemical methods. The possibility of using the modified sorbent as a drug of prolonged action is studied: tributyrin desorption from the carbon sorbent under model conditions in contact with 0.9 % NaCl (physiological solution) and in ethanol is investigated. It is established that in contact with the test solutions, the modifier deposited on the carbon carrier is desorbed within 6 h.

Keywords: porous carbon sorbent, butyric acid, tributyrin, modification, adsorption

INTRODUCTION

Search for new sources of butyric acid and the methods of its delivery into human or animal organisms is an urgent research direction. Butyric acid belongs to monocarboxylic saturated acids, it is a colourless liquid with specific strong odour, highly volatile, unstable in aqueous solutions (its formula is $C_4H_8O_2$, molecular mass 81 g/mol). The biological role of butyric acid in the organism is essential: its functions include nutritive, energy-providing, protective action in the intestines, and it possesses antibacterial properties [1–5]. However, its application in the pure form is inefficient because the major part of butyric acid is oxidized while passing through the stomach and does not reach the intestines.

A promising solution to this problem is the use of butyric acid derivatives. An example of such compounds is tributyrin (TB) – an ester of glycerol and butyric acid. Tributyrin belongs to structural lipids, it is composed of three butyrate fragments esterified with glycerol and is insoluble in water. In the organism, this compound is prone to hydrolysis under the action of lipase enzyme to form butyrate and glycerol at pH 7.5–8 [6]. Tributyrin is considered to be a low-toxic compound (corresponding to the 4th class of danger).

Many researchers report antiseptic, anti-inflammatory, wound-healing, and antioxidant properties of TB [7, 8]. It has been convincingly proved in experimental studies during recent years that the introduction of TB into the intestines causes a decrease in the production of proinflammatory cytokines and nitrogen oxide (NO), and reduces liver damage in case of endotoxemia [9].

At present, a method for providing efficient TB delivery into the organism still remains a question. This efficiency is measured as a portion of butyric acid that can reach the intestines. The method of directed drug transport allows one to increase the concentration of the agents to be delivered to definite organs and tissues, enhance

the duration and efficiency of drug action (prolonged action), and decrease side effects.

The goal of the work is to develop a method to modify carbon porous sorbent with tributyrin and investigate physicochemical properties of the obtained material. To achieve the formulated goal, the following tasks were solved: 1) to develop a procedure for TB synthesis; 2) to determine the optimal conditions and the parameters of TB sorption on the carbon support; 3) to synthesize the experimental samples of the modified sorbent and to study their physicochemical properties; 4) to investigate the possibility to use the modified sorbent as a medicinal preparation of prolonged action in model solutions.

EXPERIMENTAL

Materials

The support proposed for the delivery of TB into the organism is the porous carbon sorbent (CS) developed at the Center of New Chemical Technologies BIC (Omsk). The sorbent is characterized by the mesoporous structure (specific surface area determined using the BET procedure is 315 m^2/g, specific pore volume is 0.340 cm^3/g, mesopore volume 0.330 cm^3/g, average pore diameter 4 nm), contains insignificant amount of mineral admixtures (not more than 0.15 wt %), the prevailing granule size is 0.50 mm (93 wt %). The material is characterized by high chemical purity (carbon content not less than 98.5 wt %), biocompatibility, smooth surface relief, and spherical granule shape. Fine carbon dust is almost completely absent from its pores. This is explained by the fact that this material has been treated hydromechanically, its pH is stabilized (6.0–8.0). The carbon sorbent possesses high chemical and biological purity. Previous investigations have demonstrated that the sorbent does not injure the mucous membranes of the gastrointestinal tract, and does not destroy blood cells [10].

The modifying agent for the porous carbon sorbent was TB, 908 g/L (90.8 wt %), synthesized according to the procedure described in [11].

The following reagents were used for the synthesis of TB:

– glycerol $C_3H_5(OH)_3$ (mass fraction not less than 99 wt %, analytically pure reagent grade, according to GOST 6259-75, alt. 1, 2, LC Omskreaktiv);

– butyric (butanoic) acid $C_4H_8O_2$ (mass fraction not less than 99 wt %, pure reagent grade, according to TU 6-09-530-75, JSC EKOS-1);

– toluene $C_6H_5CH_3$ (mass fraction not less than 99 wt %, analytically pure reagent grade, according to GOST 5789-78, LC Omskreaktiv);

– orthophosphoric acid H_3PO_4 (mass fraction not less than 85 wt %, analytically pure reagent grade, according to GOST 6552-80, LC Omskreaktiv).

Tributyrin is insoluble in water, so TB solutions were prepared using ethanol C_2H_5OH (mass fraction 95 wt %, JSC Kemerovo Pharmaceutical Plant).

Methods

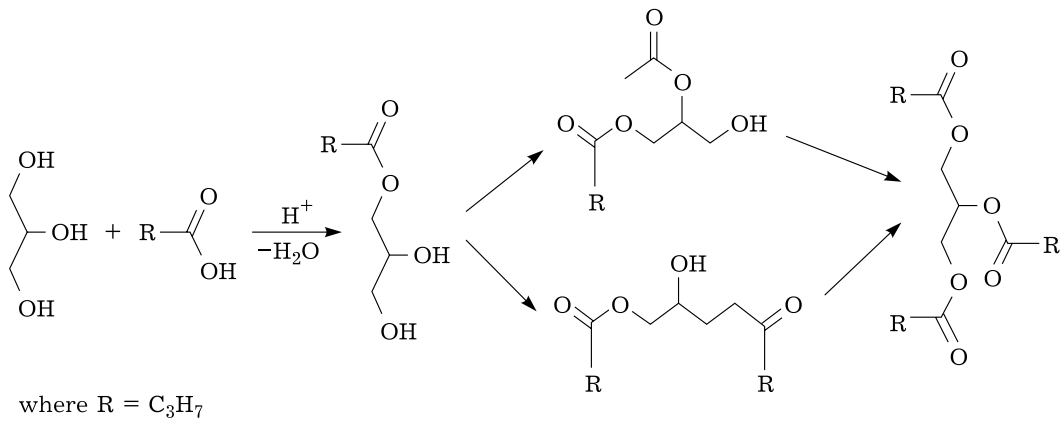
Analysis of butyric acid, glycerol, and the synthesized TB was carried out by means of nuclear magnetic resonance (NMR) ^1H, ^{13}C using an AVANCE 400 spectrometer (Bruker, USA) and gas chromatography – mass spectrometry (GC-MS) with a 6890/5973N instrument (Agilent Technologies, USA).

Investigation of the texture characteristics of sorbent samples was carried out by means of low-temperature adsorption of nitrogen (T = −195.7 °C) using a Gemini 2380 analyzer (Micromeritics, USA). Prior to adsorption measurements, the samples were kept in vacuum at a temperature of 300 °C (initial carbon sorbent sample) and 25 °C (modified samples) for 6–8 h. According to the data of nitrogen adsorption isotherm, specific surface area was calculated according to BET procedure (S_{BET}, calculation within the range P/P_0 = 0.05–0.30), total pore volume was calculated at P/P_0 = 0.96. The volume of micropores was determined using comparative t-method, mesopore volume was calculated as a difference between total pore volume and micropore volume.

Completeness of modification of the carbon sorbent with TB (wt %) was evaluated by means of thermal analysis (TG-DTG-DTA) using a DTG-60 instrument (Shimadzu, Japan) in the air at a heating rate of 10 °C/min.

Titrimetric determination of the amount of oxygen-containing groups on sample surface was carried out according to the procedure of acid-base titration using the method described by H. P. Boehm [12].

The acidity (pH) of solutions after desorption was measured with Sartorius pH-meter.



where R = C_3H_7

Scheme 1.

Procedures

Synthesis of tributyrin. Synthesis of tributyrin, the modifying agent for the carbon sorbents, was carried out by means of azeotropic esterification of glycerol and butyric acid (in the presence of toluene as azeotrope- forming agent, and 85 wt % H_3PO_4 as a catalyst) according to Scheme 1 [11]. The reference data on initial reagents and the reaction product are presented in Table 1.

The reaction mixture was heated for 12 h at the toluene boiling point (110 °C) till water evolution was complete. Then toluene was evaporated from the reaction mass at atmospheric pressure (90–95 °C, azeotrope with water) for 35–45 min, then unreacted butyric acid was removed (140–165 °C) for 45–60 min. According to the results of analyses by means of GC-MS and spectrophotometry, TB yield was 90.8 wt. % (the volume of thus synthesized TB is approximately equal to 60 mL). To achieve TB yield 97–98 wt %, it is necessary to carry out additional purification of the product by means of vacuum distillation.

Quantitative determination of tributyrin in ethanol solution. The amount of tributyrin in ethanol solutions was determined by means of spectrophotometry using a CECIL-1021 instrument (Cecil Instruments Ltd., UK) in a quartz cell with the absorbing layer thickness of 10 mm, at the wavelength of 215±5 nm. The amount of TB in the solution was calculated using the calibration plot recorded within the concentration range 0.9–2.3 g/L by diluting 400–1000 times.

Adsorption of tributyrin from ethanol solutions on the carbon sorbent. The concentration of TB in solution was determined before and after adsorption by means of spectrophotometry at room temperature. The static adsorption capacity of the adsorbent (a, mg/g) was calculated according to equation:

$$a = \frac{(C_0 - C_x) \cdot V}{m_{CS}} \quad (1)$$

where a is the amount of TB adsorbed by the carbon sorbent, g/g; C_0 and C_x are initial and equilibrium TB concentrations in the solution, respectively, g/L; V is the volume of ethanol solution, L; m_{CS} is the mass of the portion of carbon sorbent, g.

The value of a_{max} is calculated with $C_x = 0$ (the limiting theoretical adsorption value).

The corresponding degree of extraction after contact with the sorbent after 1–48 h was calculated for the obtained adsorption values:

TABLE 1

Reference data on initial reagents and reaction product

Compound	Molecular mass, g/mol	Amount of substance, mol	Density, g/cm^3	T_b, °C
Glycerol	92	0.20	1.2610	290
Butyric acid	88	1.20	0.9528	163
Toluene	92	0.22	0.8669	110
Orthophosphoric acid	98	0.01	1.6850	158
Tributyrin (product)	302	0.20	1.0320	307

$$R = \frac{a}{a_{max}} \cdot 100 \quad (2)$$

where R is the degree of TB extraction, %.

The optimal volume ratio in the system carbon sorbent – TB solution in ethanol (later referred to as (CS/TB) was determined with the initial TB concentration equal to 227 g/L. The ratio CS/TB was varied as 1 : 2, 1 : 5, 1 : 10.

The time of equilibrium for TB adsorption from ethanol solution on the initial carbon sorbent was measured within TB concentration range 114–681 g/L for 1–48 h under static conditions (with periodic mixing) at the determined optimal ratio CS/TB = 1 : 10.

The dependence of TB adsorption on initial sorbent on its concentration in the ethanol solution was studied at the equilibrium time of 24 h and the volume ratio CS/TB = 1 : 10.

TB solution in the amount of 4 mL, with the concentration 114 to 681 g/L, was added to the sorbent portion of 0.24±0.04 g, and the amount of adsorbate was determined. Adsorption value was calculated, and the dependence of adsorption on the adsorbent under investigation on the equilibrium concentration in solution was plotted.

Investigation of tributyrin desorption from the surface of the modified samples of carbon sorbent under model conditions. Investigation of the desorption of deposited TB from the surface of modified sorbent samples was carried out in the physiological solution of 0.9 wt % NaCl and in ethanol solution under static conditions at the sorbent/ ethanol solution ratio equal to 1 : 10 (by volume), for 24–48 h. Determination of solution pH after the contact with the sorbent samples under investigation was carried out after 0.5–48 h. The amount of TB transferred into the ethanol solution from the sorbent surface was determined by means of spectrophotometry in the UV region using the obtained calibration plot.

Investigation of changes in pH of solutions modeling biological media of stomach and intestines after the contact with modified sorbents was carried out under static conditions at the sorbent (g)/solution (mL) ratio equal to 1 : 10, at a temperature of 36±2 °C for 24–48 h. To simulate the medium in stomach, a 0.02 M HCl solution with pH 1.7 was used, intestinal medium was simulated by a solution of 0.025 M $NaHCO_3$ with pH 8.5.

RESULTS AND DISCUSSION

Synthesis of tributyrin

The products of TB synthesis were studied by means of ^1H and ^{13}C NMR and GC-MS. A ^1H NMR spectrum of the products of glycerol esterification with butyric acid is presented as an example in Fig. 1.

The recorded ^1H NMR spectra demonstrated the presence of the major reaction product – TB (signals with chemical shifts 5.5, 4.5, 2.5, 1.75, 1.25 ppm correspond to definite hydrogen atoms in TB structure) and the residual unreacted butyric acid, which was taken in excess for reaction (the signal with chemical shift 10.85 ppm corresponds to hydrogen atom bound with carboxyl group). Calculation of the percentage of TB according to NMR data is hindered due to superposition of signals from initial butyric acid and from the reaction product.

Gas chromatography – mass spectrometry allowed quantitative determination of the yield of synthesis products and revealed initial butyric acid and glycerol monoester against the trimester formed as the major product. The yield of the target product TB synthesized according to the chosen procedure was 91 %, the yield of side products (monobutyrin) was 3 %, the admixture of initial butyric acid was 6 %. We suppose that these admixtures would not have any substantial effect on the modification of sorbent surface because they would not have any negative effect on human organism: butyric acid and its derivatives are considered as low-toxic compounds [1, 3, 7].

Vacuum distillation of the obtained product for the purpose of enhancing the yield of target product, TB, showed that initial butyric acid is also present in the product, but in smaller amount (2–3 wt %, results of GC-MS and NMR spectroscopy). The concentration of the target product was 97–98 %. However, to achieve this yield, a more complicated apparatus arrangement is necessary, the process is labour-intensive and not very reasonable.

Thus, TB without additional distillation stage was used to modify the carbon sorbent.

Investigation of the adsorption properties of carbon sorbent with respect to tributyrin

To determine the conditions and parameters for the modification of initial carbon sorbent, we studied the adsorption characteristics of the material with respect to TB. The tasks were: to determine the optimal adsorption conditions under

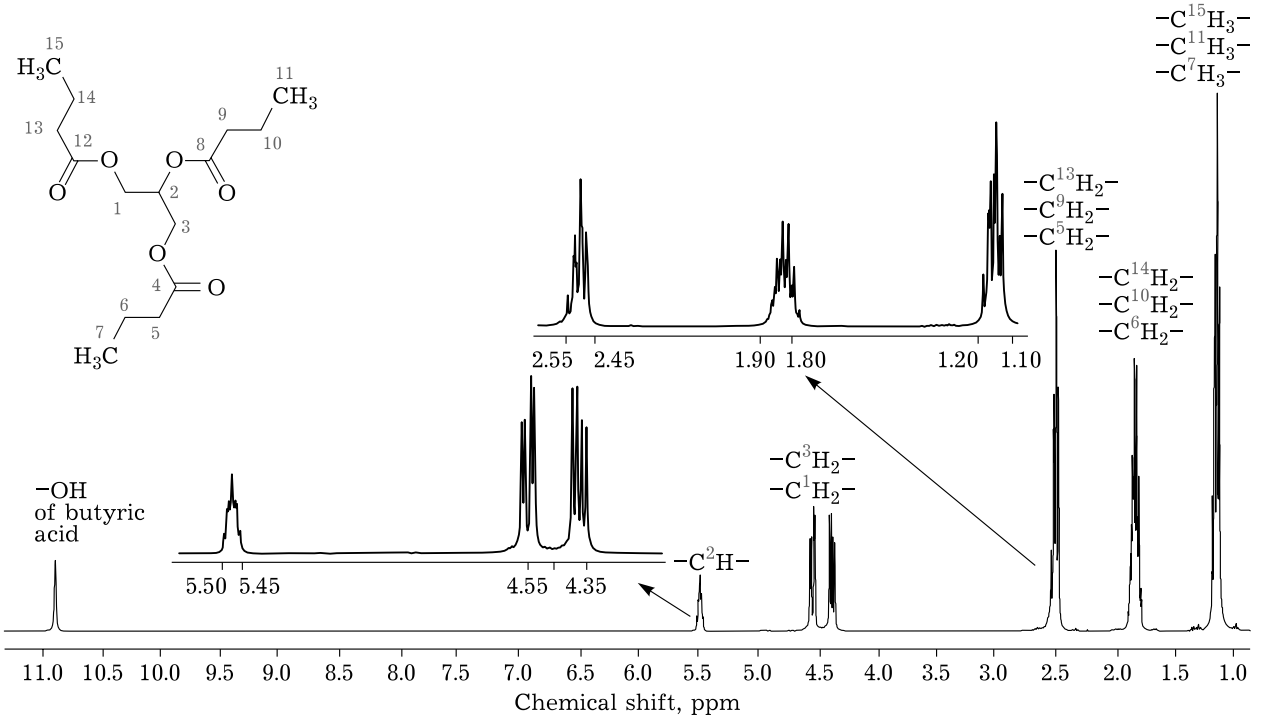


Fig. 1. ^{1}H NMR spectrum of the products of esterification of glycerol with butyric acid.

which the maximal TB adsorption on the porous carbon sorbent is achieved, namely the sorbent/modifying agent ratio, equilibrium time, the concentration of the modifying agent.

To determine TB in ethanol solutions quantitatively, a calibration graph was plotted: $D = 0.7019C_x + 0.0768$ (correlation coefficient $R^2 = 0.998$), where D is the optical density of solution, C_x is TB concentration in ethanol, g/L. The linearity of the calibration plot is observed within TB concentration range 0.9–2.3 g/L.

It is established that the optimal volume ratio in the system CS/TB at TB concentration 227 g/L after 24 h is 1 : 10, adsorption value is 2.77 g/g (recovery degree 70 %). Results are presented in the form of adsorption curves (Fig. 2, *a*). Analysis of the obtained data shows that the time of equilibrium in the system CS/TB is established within 24 h at any ratio under investigation.

We studied the time within which the equilibrium of TB adsorption on the carbon sorbent is established, within the concentration range of aqueous TB solutions 114–681 g/L at the determined CS/TB ratio equal to 1 : 10. The obtained results are presented in Fig. 2, *b*.

It is demonstrated that within TB concentration range 114–454 g/L the time of equilibrium in the system CS/TB at the ratio of 1 : 10 is 24 h. With an increase in TB concentration from 114 to 681 g/L, a regular increase in the maximal TB adsorption value from 1.35 to 5.68 g/g is observed.

The isotherm of TB adsorption on the sorbent under investigation was obtained (Fig. 3) for the determined equilibrium time (24 h).

According to the classification of adsorption isotherms proposed by C. H. Giles for adsorption from solutions on solid surface, the graphical view of the isotherm of TB adsorption on the carbon surface corresponds to L3 kind, when adsorption continues also after monolayer is filled, which may be due to the polymolecular adsorption or reorientation of the molecules with respect to sorbent surface [13, 14].

Synthesis of the samples of carbon sorbent modified with tributyrin

According to the results of adsorption studies, the optimal conditions were chosen for carbon sorbent modification with TB: the ratio CS/TB is equal to 1 : 10, duration of impregnation is 24 h, room temperature, static conditions. Two samples of carbon sorbent were made: CS-TB-1 and CS-TB-2, both of them were impregnated with ethanol solutions of TB with initial concentrations 114 g/L (equilibrium concentration 11 g/L, adsorption value 1.35 mg/g) and 227 g/L

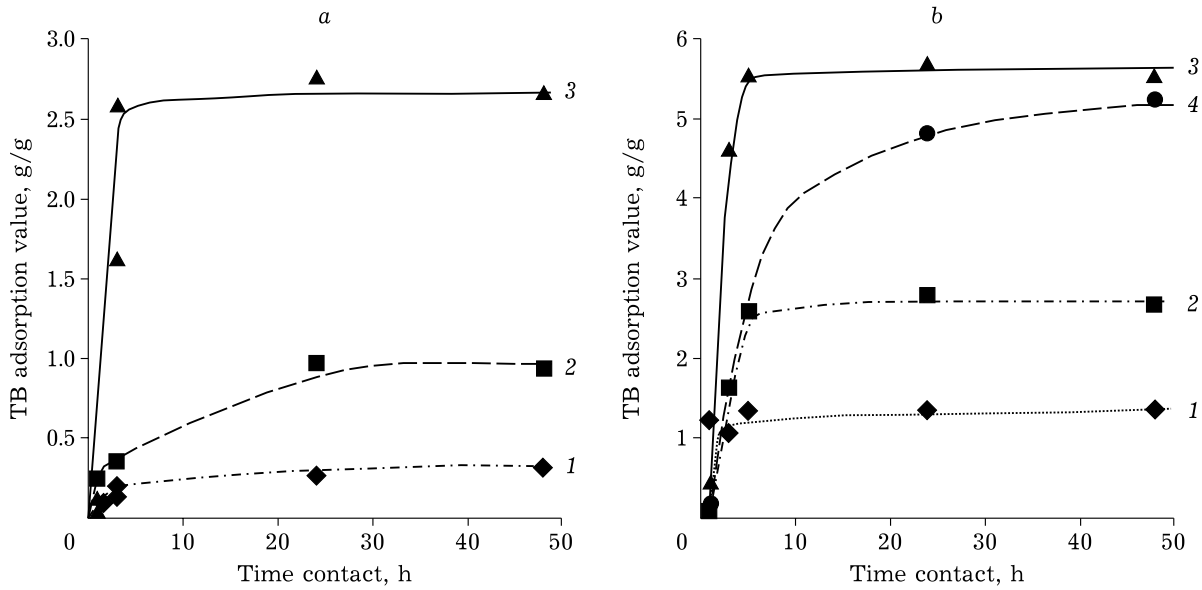


Fig. 2. Dependence of the adsorption of tributyrin (TB) on the time of contact with carbon sorbent (CS): *a* – for different CS/TB ratios: 1 : 2 (*1*), 1 : 5 (*2*), 1 : 10 (*3*) (initial TB concentration 227 g/L); *b* – for variations of initial TB concentration, g/L: 114 (*1*), 227 (*2*), 454 (*3*), 681 (*4*) (the ratio CS/TB = 1 : 10).

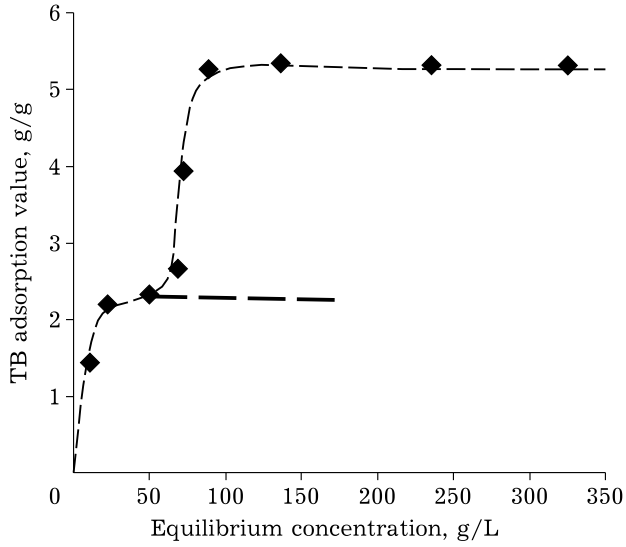


Fig. 3. Adsorption isotherm for tributyrin (TB) on the carbon sorbent (CS) under investigation (the ratio CS/TB = 1 : 10, contact time 24 h).

(equilibrium concentration 69 g/L, adsorption value 2.66 mg/g), respectively.

Modification conditions: TB solution in ethanol, with the necessary concentration, was added to the portion of carbon sorbent at a ratio CS/TB equal to 1 : 10, and the mixture was kept under static conditions (the sorbent was impregnated) at room temperature for 24 h, then the sorbent was dried, at first in the air for 24 h, and then in a tubular furnace in the atmosphere of argon for 2 h at a temperature of 105 °C to achieve complete removal of ethanol vapour.

Physicochemical properties of the modified carbon sorbent

Results of the studies of texture characteristics of the samples under investigation are presented in Table 2 and in Fig. 4. One can see that modification of the carbon sorbent with TB involves pore filling, which leads to a decrease in specific surface area and total pore volume. For the CS-TB-1 sample, specific surface area decreases by a factor of 5.6, while total pore volume decreases by a factor of 2.5; for the CS-TB-2 sample, a decrease in more substantial: by a factor of 19.6 and 3.2, respectively. The samples of carbon sorbent after modification conserve their mesoporous structure, because capillary-condensation hysteresis is observed in the adsorption isotherms of modified samples, similarly to those for the initial sorbent (see Fig. 4).

According to the data of thermogravimetric analysis (TG), it is established that there are no mass changes in the thermogram of initial sample (CS) within temperature range 25–500 °C (Fig. 5, *a*, curve *3*), heat effects are absent from the curve of differential thermal analysis (DTA) (see Fig. 5, *b*, curve *3*). So, thermal stability of non-modified carbon sorbent under heating to 500 °C is confirmed.

According to the data of TG analysis of the modified samples, it is established that the per-

TABLE 2

Texture characteristics of carbon sorbent samples under investigation

Sample	Concentration of initial modifier solution, g/L	Specific surface area, m^2/g	Total pore volume, cm^3/g	Volume of mesopores, cm^3/g	Volume of micropores (t-method), cm^3/g	Average pore diameter, nm
CS	–	315	0.340	0.330	0.010	4
CS-TB-1	114	56	0.135	0.135	–	8
CS-TB-2	227	16	0.106	0.106	–	20

Note. The average value of specific surface area of the samples under investigation is indicated, calculated from the experimental results obtained for all synthesized samples.

centage of the modifying agent for sample CS-TB-1 is 14.2 wt %, for sample CS-TB-2 – 28.2 wt % (see Fig. 5, *a*), which agrees with the results obtained by measuring the specific surface area of samples (see Table 2). According to DTA curves, exothermal decomposition of TB supported as the modifying agent occurs within the temperature range 250–350 °C, with a maximum at 320 °C (see Fig. 5, *b)*.

The content of oxygen-containing groups on the surface of sorbents modified with TB was determined by means of the method based on titration and proposed by H. P. Boehm. The results are presented in Table 3. It is determined that the content of oxygen-containing groups on the modified samples is substantially higher than that on non-modified sorbent CS (by a factor of 1.4–3.7). The largest amount of total phenol groups is obtained for the sample with the largest amount of the modifying agent CS-TB-2.

The possibility of migration (desorption) of the deposited modifier from the surface of the carbon sorbent was studied. The obtained data allow evaluation of the possibility of prolonged action of the biologically active substance – TB deposited on the carbon support.

Investigation of desorption of the modifier from the samples of carbon sorbents CS-TB-1 and CS-TB-2 was carried out in the physiological solution (0.9 % aqueous solution of NaCl) and in the solution in ethanol (EtOH). Solution pH was determined after contacts with the sorbents under investigation, 0.5–24 h later (Table 4).

It is shown that the contact of sorbent samples with physiological solution causes a decrease in pH by 3–4 units even within 30 min. The ob-

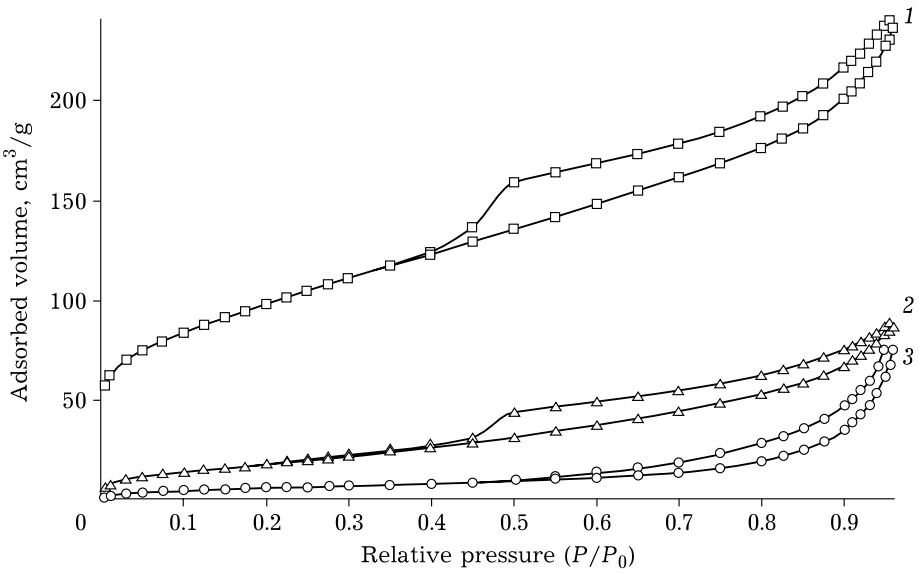


Fig. 4. The isotherm of nitrogen adsorption-desorption on carbon sorbents under investigation: CS (*1*), CS-TB-1 (*2*) and CS-TB-2 (*3*).

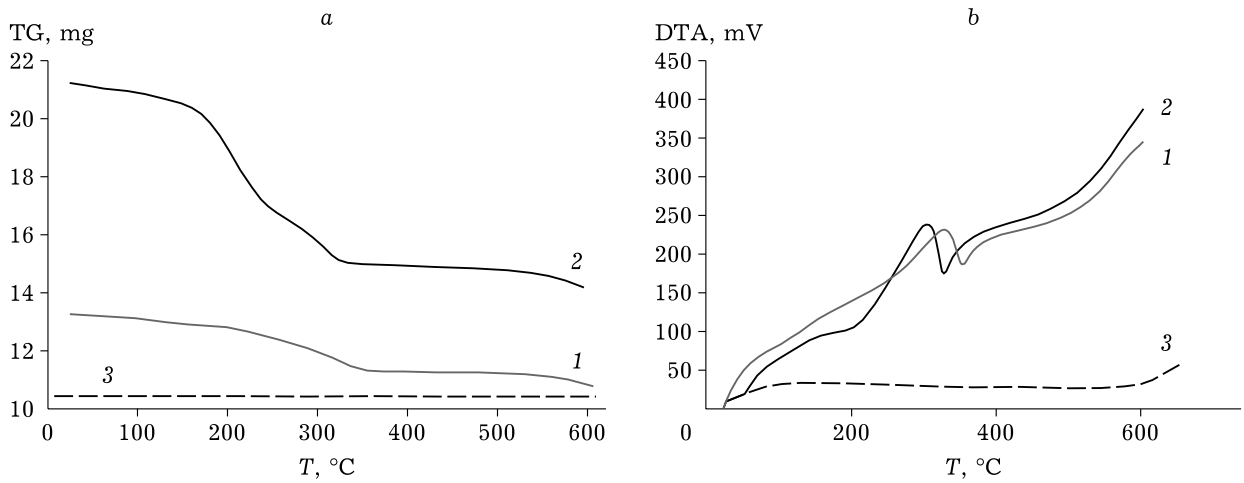


Fig. 5. Results of thermal analysis (*a*), differential thermal analysis (*b*) for the samples of carbon sorbent CS-TB-1 (*1*), CS-TB-2 (*2*) and initial sample CS (*3*).

served changes in pH may be explained by the hydrolysis of TB deposited on sorbent surface, to form butyric acid.

TB desorption from sorbent surface in the ethanol solution proceeds within 1 h (see Table 4). The quantitative determination of TB in the ethanol solution after contact with modified samples shows that TB adsorption-desorption equilibrium is established within 6 h (Table 5).

Results of the investigation of acidity of the solutions simulating biological media of stomach (0.02 M HCl) and intestines (0.025 M $NaHCO_3$) for the samples of initial (CS) and modified (CS-TB-1 and CS-TB-2) carbon sorbents are presented

TABLE 3

Oxygen-containing groups on the surface of carbon sorbents

Parameter	Sample		
	CS	CS-TB-1	CS-TB-2
Concentration of initial modifier solution, g/L	–	114	227
Total amount of oxygen-containing groups, mmol/g	0.065	0.089	0.243
Amount of carboxylic groups, mmol/g	0.032	0.039	0.079
Amount of phenol groups, mmol/g	0.033	0.050	0.164

TABLE 4

Dependence of acidity on contact time in the studies of tributyrin desorption in physiological solution and in ethanol

Sample	Contact time, h								
	0	0.5	1	2	4	6	18	24	48
pH during the contact of sorbent with physiological solution									
CS	6.31	6.31	6.31	6.32	6.32	6.31	6.31	6.31	6.32
CS-TB-1	6.31	3.55	3.46	3.35	3.29	3.29	3.55	3.29	3.29
CS-TB-2	6.31	3.36	3.29	3.20	3.18	3.11	3.06	2.96	2.99
pH during the contact of sorbent with ethanol solution									
CS	7.83	7.83	7.82	7.83	7.83	7.83	7.82	7.82	7.82
CS-TB-1	7.83	3.74	3.71	3.57	3.50	3.48	3.53	3.47	3.47
CS-TB-2	7.83	3.56	3.47	3.33	3.32	3.26	3.26	3.26	3.38

Note. Here and in Table 6: Initial pH for the solution under investigation before contact with the sorbent is shown in the first column (contact time 0 h).

TABLE 5

Tributyrin concentration in ethanol solution after contact with the modified samples of carbon sorbent

Sample	Desorption time, h						
	1	2	3	4	5	6	24
CS-TB-1	76.1	70.2	77.8	82.4	76.1	70.2	66.6
CS-TB-2	172.0	131.7	178.8	184.4	178.8	131.7	135.4

TABLE 6

Dependence of acidity (pH) on contact time in the studies of tributyrin desorption in model solutions

Sample	Model solution	Contact time, h						
		0	1	2	4	6	24	48
CS	HCl	1.74	1.81	1.82	1.84	1.84	1.90	1.90
	$NaHCO_3$	8.40	8.62	8.74	8.82	8.86	8.91	9.05
CS-TB-1	HCl	1.88	1.78	1.80	1.86	1.86	1.81	1.81
	$NaHCO_3$	8.35	8.63	8.69	8.74	8.87	8.90	9.01
CS-TB-2	HCl	1.90	1.86	1.85	1.86	1.86	1.88	1.87
	$NaHCO_3$	8.69	8.74	8.85	8.90	8.94	9.00	9.03

Note. See Table 4.

in Table 6. Changes in solution pH in the acid medium after contact with sorbents are insignificant. In the alkaline medium, changes in pH for the non-modified and modified samples were comparable. So, it may be assumed that hydrolysis if TB to butyric acid does not proceed in acid and alkaline media.

For the sample of modified carbon sorbent CS-TB-2, after desorption for 48 h, investigations were carried out by means of thermal analysis and low-temperature nitrogen adsorption. It is established that the amount of deposited modifier decreases from 28.2 to 6.3 wt. % during TB desorption from the surface of the carbon sorbent, and specific surface area of the sample regularly increases from 16 to 195 m^2/g.

CONCLUSION

The synthesis of TB has been carried out. Adsorption properties of the carbon porous sorbent with respect to TB have been investigated. The optimal volume ratio in the system CS/TB is determined to be 1 : 10, and equilibrium adsorption time is 24 h. According to the classification of the isotherms of adsorption from solution on a solid surface proposed by C. H. Giles, the graphical appearance of the isotherm of TB adsorption from solution on the carbon sorbent corresponds to L3 kind, when adsorption continues after filling the monolayer, which may be due to polymolecular adsorption or reorientation of the molecules with respect to sorbent surface.

A procedure has been developed for the modification of carbon sorbent with the solution of TB in ethanol. Two samples of carbon sorbents modified with TB were obtained. The modified sample CS-TB-2 is of the highest interest. It is determined that ~28 wt % of the modifier is deposited onto this sorbent. The sample CS-TB-2 possesses specific surface area 16 m^2/g and has oxygen-containing groups on its surface (total content of carboxylic and phenol groups is 0.243 mmol/g, among them carboxylic groups account for 0.079 mmol/g, phenol groups – 0.164 mmol/g). In contact with the solutions under investigation, TB deposited on the carbon support is desorbed gradually within 6 h. In this process, the amount of deposited modifier decreases from 28.2 to 6.3 wt %, and the specific surface area of the sample increases regularly from 16 to 195 m^2/g. It is demonstrated that CS-TB-2 sample is the most promising material to be applied for the purpose of enterosorption.

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REFERENCES

1 Mirzaei R., Afaghi A., Babakhani S., Sohrabi M. R., Hosseini-Fard S. R., Babolhavaeji K., Akbari S. K. A., Yousefimashouf R., Karampoore S., Role of microbiota-derived short-chain fatty acids in cancer development and prevention, *Biomed. Pharmacother.*, 2021, Vol. 139, Art. 111619.

2 Litvak Y., Byndloss M. X., Bäumler A. J., Colonocyte metabolism shapes the gut microbiota, *Science*, 2018, Vol. 362, No. 6418, Art. eaat9076.

3 Gotkhals L, Gorbakova A., Growth stimulants based on butyric acid for pig breeding, *Compound Feed*, 2015, Vol. 9, P. 92–95. (In Russ.).

4 Luo H., Yang R., Zhao Y., Wang Z., Liu Z., Huang M., Zeng Q., Recent advances and strategies in process and strain engineering for the production of butyric acid by microbial fermentation, *Bioresour. Technol.*, 2018, Vol. 253, P. 343–354.

5 Erofeev N. P., Radchenko V. G., Seliverstov P. V., Clinical Physiology of the Colon. Mechanisms of Action of Short-chain Fatty Acids in Normal and Pathological Conditions, Forte Print, St. Petersburg, 2012. (In Russ.).

6 Fernandes T. V., Keesman K. J., Zeeman G., van Lier J. B., Effect of ammonia on the anaerobic hydrolysis of cellulose and tributyrin, *Biomass Bioenergy*, 2012, Vol. 47, P. 316–323.

7 Kovanda L., Zhang W., Wei X., Luo J., Wu X., Atwill E. R., Vaessen S., Li X., Liu Y., *In vitro* antimicrobial activities of organic acids and their derivatives on several species of gram-negative and gram-positive bacteria, *Molecules*, 2019, Vol. 24, No. 20, Art. 3770.

8 Kang S. N, Lee E., Lee M. K., Lim S. J., Preparation and evaluation of tributyrin emulsion as a potent anti-cancer agent against melanoma, *Drug Deliv.*, 2011, Vol. 18, No. 2, P. 143–149.

9 Miyoshi M., Sakaki H., Usami M., Iizuka N., Shuno K., Aoyama M., Usami Y., Oral administration of tributyrin increases concentration of butyrate in the portal vein and prevents lipopolysaccharide-induced liver injury in rats, *Clin. Nutr.*, 2011, Vol. 30, No. 2, P. 252–258.

10 P'yanova L. G., Likholobov V. A., Sedanova A. V., Drozdetskaya M. S., Fundamental technological approaches to the synthesis of carbon sorbents for medical and veterinary applications, *Russ. J. Gen. Chem.*, 2020, Vol. 90, No 3, P. 550–558.

11 Safronov S. P., Ester plasticizing compositions from renewable vegetable raw materials, Thesis for Cand. Sci. in Chemistry, Samara, 2016. (In Russ.).

12 Boehm H. P., Surface oxides on carbon and their analysis: A critical assessment, *Carbon*, 2002, Vol. 40, No. 2, P. 145–149.

13 Alaqarbeh M. M., Adsorption phenomena: Definition, mechanisms, and adsorption types: Short review, *RHAZES: Green and Applied Chemistry*, 2021, Vol. 13, P. 43–51.

14 Practical Course in Physical Chemistry, NSU. Chemical Thermodynamics and Kinetics. Adsorption from Solutions on Solid Surface: Methodical Guide, Netskina O. V.(Ed.), Editing and Publishing Centre, NSU, Novosibirsk, 2015. (In Russ.).