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RESEARCH ARTICLE

On the stability of characteristics of cellulose diacetate solutions with an iodine-containing radiopaque substance and solid emboli on their basis

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Abstract

Objectives. Among the materials used for embolization, liquid embolizing agents based on solutions of biocompatible polymers attract particular interest. Such compositions are capable of targeting and reliably occluding a branched vascular network by forming solid emboli directly in the patient's body. The safety and effectiveness of such materials are determined by the stability of the initial composition and the resulting emboli. This article presents a long-term study of the stability of embolizing solutions of a polymer (cellulose diacetate) and a radiopaque additive iohexol in dimethyl sulfoxide, as well as emboli based thereon, in aqueous media.

Methods. The stability of the initial solutions exposed to 60°C for 45 days (“accelerated aging” corresponding to three years of storage at 23 ± 2°C) was studied by rotational viscometry using a Brookfield DV2T RV rotary viscometer equipped with a working unit in the form of two coaxial cylinders and by ultraviolet-visible spectrophotometry using a Cary 60 UV-Vis spectrophotometer. The long-term stability of emboli in aqueous media was studied by gel permeation chromatography using a Gilson chromatograph (Japan) with refractometric detection and by gas chromatography using an Agilent 6890N chromatograph with a DB-5MS column (30 × 0.25 × 0.5 μm), equipped with an Agilent 5973 N mass spectrometric detector.

Results. During “accelerated” storage of cellulose diacetate and iohexol solutions in the dark, no changes in the viscosity coefficient (0.268 ± 0.0049 Pa·s at 25°C) and the quantitative content of bound iodine (50.1 ± 1.0 mg/mL) were observed. However, when iohexol solutions in dimethyl sulfoxide were stored under daylight, free iodine was separated in minor quantities. When emboli consisting of cellulose diacetate were stored in an aqueous medium for eight years, the molecular weight of the polymer (60 kDa) remained unchanged. The degradation products of cellulose diacetate, expected in the aqueous extract, were also absent.

Conclusions. The model embolic composition consisting of cellulose diacetate and iohexol in dimethyl sulfoxide is stable when stored in the absence of light. The as-formed solid emboli remain stable for at least eight years when stored in an aqueous environment.

Keywords

embolization, embolic agent, stability, cellulose acetate, iohexol, dimethyl sulfoxide

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НАУЧНАЯ СТАТЬЯ

О стабильности характеристик растворов диацетата целлюлозы с йодсодержащим рентгеноконтрастным веществом и твердых эмболов на их основе

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Аннотация

Цели. Среди используемых материалов для эмболизации большой интерес представляют жидкие эмболизирующие агенты на основе растворов биологически совместимых полимеров. Такие композиции способны осуществлять надежную преднамеренную окклюзию разветвленной сосудистой сети благодаря формированию твердого эмбола непосредственно в организме пациента. Для обеспечения безопасности и эффективности такого материала важны стабильность исходного состава и итогового эмбола. Целью работы являлось долговременное изучение стабильности эмболизирующих растворов полимера (диацетата целлюлозы) и рентгеноконтрастной добавки йогексола в диметилсульфоксиде, а также эмболов на их основе, выдержанных в водной среде.

Методы. Исследование стабильности исходных растворов, выдерживаемых в течение 45 суток при температуре 60°C («ускоренное старение», соответствующее трем годам хранения при 23 ± 2°C), проводили методом ротационной вискозиметрии на ротационном вискозиметре *Brookfield DV2T RV* с рабочим узлом в виде двух коаксиальных цилиндров и методом спектрофотометрии в ультрафиолетовой и видимой областях спектра при помощи спектрофотометра *Cary 60 UV-Vis*. Долговременную стабильность эмболов в водных средах исследовали методом гель-проникающей хроматографии на хроматографе *Gilson* (Япония) с рефрактометрическим детектированием и методом газовой хроматографии на хроматографе *Agilent 6890 N* с колонкой *DB-5MS* (30 × 0.25 × 0.5 мкм), снабженным масс-спектрометрическим детектором *Agilent 5973 N*.

Результаты. Показано, что при «ускоренном» хранении растворов диацетата целлюлозы и йогексола в темноте не наблюдались изменения коэффициента вязкости (0.268 ± 0.0049 Па·с при 25°C) и количественного содержания связанного йода (50.1 ± 1.0 мг/мл). Однако при хранении растворов йогексола в диметилсульфоксиде при естественном освещении отщеплялся свободный йод в малых количествах. При хранении эмболов, состоящих из диацетата целлюлозы, в водной среде в течение восьми лет, молекулярная масса полимера (60 кДа) не изменилась. В вытяжке водной среды также отсутствовали предполагаемые продукты деструкции диацетата целлюлозы.

Выводы. Модельный эмболизирующий состав, состоящий из диацетата целлюлозы и йогексола в диметилсульфоксиде, является стабильным при хранении в отсутствии света. Сформированные твердые эмболы при хранении в водной среде остаются стабильными по крайней мере в течение восьми лет.

Ключевые слова

эмболизация, эмболизирующий агент, стабильность, ацетат целлюлозы, йогексол, диметилсульфоксид

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INTRODUCTION

Embolization of blood vessels is defined as their targeted blockage by specially injected substrates, referred to as emboli [1, 2]. The objective of this procedure is to obliterate a specified area of arteriovenous discharge without compromising the circulation of normal tissues. Embolic vascular closure can be performed at any level, ranging from large arteries or veins to capillaries [3].

Embolization represents a contemporary trend in the management of a wide range of clinical conditions, including angiodysplasia (congenital vascular abnormalities), aneurysms, varicose veins, etc. Moreover, embolization plays a pivotal role in the treatment of oncological diseases, being an efficacious method of preoperative preparation of patients for subsequent surgical intervention with minimal blood loss [4–7]. Such a procedure is minimally invasive, which is a great advantage. The safety and effectiveness of embolization depend primarily on the surgeon's experience, optimal technical equipment, and, to a lesser extent, on the characteristics of embolizing drugs [8].

Today, there exist various types of embolizing agents [9, 10], including initially solid substrates (gel foam, microparticles, etc.) and structures (spirals, cylinders, occluders), or liquid agents. Among the latter are sclerosing (ethanol, sotradecol, etc.) and polymerizing (cyanoacrylates and other acrylic monomers) substances as well as non-adhesive polymer solutions that are converted into solid emboli already in the patient's body. These agents offer significant advantages due to their capacity to penetrate complex vascular branches, successfully blocking blood vessels in the very center of the vascular lesion without damaging these vessels. As stated in [11], the primary components of such formulations are biologically compatible elements, namely polymer, water-soluble solvent, and radiopaque substances.

The works [12–14] demonstrated the potential of utilizing cellulose acetate—a natural and biologically compatible polymer—as a polymer base for liquid embolizing agents. Its clinical use in the composition of liquid embolizing agents was described, e.g., in [15–17]. Dimethyl sulfoxide, a well-known nonpolar aprotic solvent with anti-inflammatory, antioxidant, and analgesic properties, is widely employed as a solvent for such systems [18, 19]. The radiopaque component is typically composed of a metal powder, most commonly micronized tantalum particles [20, 21], or organic iodine-containing substances, either aliphatic or aromatic in nature [21, 22].

Metal powders ensure effective visualization of the embolus; however, they are an insoluble dispersed phase in a relatively low-viscosity polymer solution. This phase is known to settle readily and is distributed unevenly in the embolizing agent when injected into a blood vessel, resulting in artefacts during subsequent visualization of the embolus in the patient's body [20, 21]. Conversely, iodized aliphatic derivatives demonstrate limited solubility in water and are characterized by a gradual absorption rate into the tissues of living organisms. However, when administered in conjunction with dimethyl sulfoxide, these derivatives exhibit the capacity to liberate free iodine, a process that has been shown to exert deleterious effects on living tissues [23–25]. For comparison, commercially available aromatic iodine derivatives are water-soluble substances, capable of penetrating the extracellular space relatively easily without causing significant complications [26]. In view of that, we employed an iodinated aromatic derivative as a contrasting agent for polymer solutions in dimethyl sulfoxide, a method which provides temporary radiopaque emboli.

When evaluating the efficacy of embolizing pharmaceuticals, the stability of the initial liquid formulation during storage and the behavior of the emboli formed therefrom under conditions analogous to those encountered within a living organism are critical aspects. These parameters determine the shelf life of the liquid embolizing agent and the duration of contact of the hardened embolus with the patient's body. In light of this, our objective was to study the long-term stability of solutions of cellulose diacetate and iohexol in dimethyl sulfoxide, as well as emboli formed on their basis, aged in an aqueous medium.

MATERIALS AND METHODS

The research objects were solutions of Xeniton cellulose diacetate (*Institute of Pharmaceutical Technologies, Russia*) in dimethyl sulfoxide (chemically pure) (*Tula Pharmaceutical Factory, Russia*) with the addition of radiopaque substance 5-[acetyl(2,3-dihydroxypropyl)amino]-*N,N'*-bis(2,3-dihydroxypropyl)-2,4,6-triiod-1,3-benzenedicarboxamide (iohexol) (*Zhejiang Haichang Pharmaceutical Co., China*), CAS 66108-95-0. Modified polyethylene glycol-4000 (up to 4.5 wt %) cellulose diacetate of the Xeniton brand with an average molecular weight of $M_n = 60 \pm 2$ kDa and an average content of acetyl groups of 2.2 ± 0.1 mol/unit was used as a polymer. The structural formulas of the repeating unit of the polymer and the iohexol molecule are shown in Fig. 1.

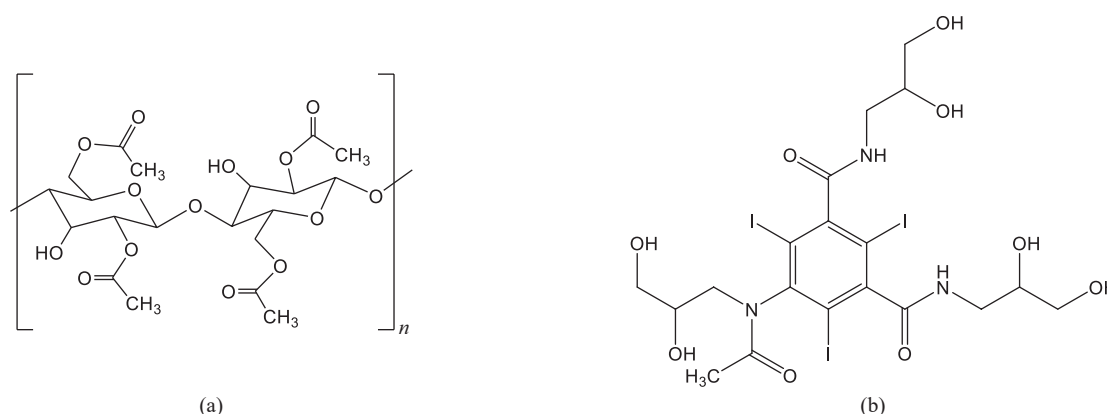


Fig. 1. Structural formulas of the main components of the studied systems: (a) cellulose diacetate unit; (b) iohexol

The research solutions were prepared by long-term (2–3 days) dissolution of cellulose diacetate in dimethyl sulfoxide at $23 \pm 2^\circ\text{C}$ until a homogeneous transparent solution was formed. After that, iohexol was added to the solution upon thorough mixing. The component ratio was polymer/iohexol/dimethyl sulfoxide = 6 : 10 : 84 wt %. The resulting solutions were purged with an inert gas (argon) or left in contact with air, hermetically sealed and kept in a thermostat at $60.0 \pm 0.1^\circ\text{C}$. The solutions were examined (each time a new sample was taken) every 7.5 days for 45 days by rheoviscometry using a Brookfield DV2T RV rotary viscometer (Brookfield Corporation, Canada) and ultraviolet–visible (UV–Vis) spectrophotometry using a Cary 60 UV–Vis spectrophotometer (Agilent Technologies, USA). In addition, the state of iohexol in solutions kept in the natural diffused sunlight was studied by UV–Vis spectrophotometry.

The as-obtained solutions were used to fabricate emboli models by means of a 1-mL syringe without a needle. The solution was compressed into 20-mL distilled-water buckets, which were obtained via a water distilling apparatus. The exposure time in water was approximately three days, with the water being changed twice. Following a period of three days, the resulting embolus was extracted and, without undergoing desiccation in the atmosphere, was subjected to a process of lyophilization. The resulting dry embolus was crushed, dissolved in tetrahydrofuran (Merck, Germany), and examined by gel permeation

chromatography. The aqueous medium from the embolus was lyophilized; the resulting dry residue was dissolved in *n*-hexane (LenReactive, Russia) and studied by gas chromatography with mass spectrometry. Emboli for long-term storage in an aqueous environment (for eight years) were prepared using a similar method, although without the addition of iohexol.

The viscosity characteristics of polymer and iohexol solutions in dimethyl sulfoxide were determined using a Brookfield DV2T RV rotary viscometer equipped with a coaxial cylinder working unit (Brookfield Corporation, Canada). The measurements were carried out at a constant temperature of $25.0 \pm 0.1^\circ\text{C}$, maintained by a TC-505MX-230 liquid thermostat (Brookfield Corporation, Canada), in the modes of stepwise increase and decrease of the shear rate.

The concentration of bound iodine was determined by UV–Vis spectrophotometry in accordance with the established procedure [23]. Spectra were obtained in quartz cuvettes within the wavelength range of 190–600 nm. Pure dimethyl sulfoxide was utilized as a reference sample. For the purposes of analysis, the initial solutions were subjected to dilution with dimethyl sulfoxide, yielding concentrations of 0.25 mg/mL.

Freeze-dried emboli or aqueous media were obtained using a Harvest Right freeze dryer (USA). For the purpose of lyophilization, the samples were subjected to a freezing process followed by drying; the process was executed in accordance with the scheme described in Table 1.

Table 1. Sample lyophilization mode

Stage	1	2	3	4	5	6
Temperature, °C	–40	–20	–5	0	10	20
Vacuum pump on/off	–	+	+	+	+	+
Time, h	2	5	5	10	10	6

The molecular mass characteristics of the emboli polymer were studied by gel permeation chromatography using a Gilson chromatograph (Japan) with refractometric detection. The analysis was performed at a temperature of 25°C in tetrahydrofuran with a flow rate of 1.0 mL/min. To separate and identify polymer fractions, an Agilent PLgel 5 μm MIXED B column (separating capacity 500–3000 kDa) was used, which was calibrated according to polystyrene standards with molecular weights of 2940, 10110, 28770, 74800, 230900, and 1390000 g/mol and a polydispersity index of less than 1.12. A solution of embolus lyophilizate in tetrahydrofuran with a polymer concentration of 0.7–10 mg/mL was prepared for analysis.

Gas chromatography experiments were performed using an Agilent 6890N chromatograph (Agilent Technologies, USA) with a DB-5MS column (30 × 0.25 × 0.5 μm) equipped with an Agilent 5973 N (gas chromatography–mass spectrometry, GC–MS) mass spectrometric detector. Helium was used as the carrier gas, with a feed rate of 1 mL/min. Injection was carried out at 250°C. A solution of aqueous lyophilizate over an embolus in *n*-hexane with a lyophilizate concentration of 1 mg/mL was prepared for analysis.

RESULTS AND DISCUSSION

At the first stage of analysis, we investigated the stability of the initial solutions of the polymer with iohexol in dimethyl sulfoxide. The control was carried out according to two main indicators—the dynamic viscosity of the solutions and the content of bound iodine in these solutions. It was previously shown that all the studied solutions exhibit Newtonian flow under the conditions studied and can be characterized by a constant coefficient of Newtonian viscosity.

Characteristic dependencies of the Newtonian viscosity coefficient (0.268 ± 0.0049 Pa·s at 25°C) and the bound iodine content (50.1 ± 1.0 mg/mL) are shown in Fig. 2. It can be seen that exposure for at least 45 days at a temperature of 60°C does not lead to changes in these parameters. In other words, the studied solutions of polymer with iohexol in dimethyl sulfoxide are stable under the conditions of exposure to a thermostat (in the dark). The contacting gaseous medium (argon or air) had no effect on the results. According to GPM 1.1.0009.15¹, for climate zone II, this corresponds to three years of storage under natural conditions (25°C at a relative humidity of 60%).

Conversely, our preliminary observations indicated that iohexol solutions in dimethyl sulfoxide exhibit

a yellowing tendency in the presence of light over time (a phenomenon not observed when stored in the dark). The investigation focused on the behavior of iohexol solutions in dimethyl sulfoxide, utilizing UV–Vis spectrophotometry (Fig. 3). The study revealed the separation of a minimal amount of iodine during a week-long storage period in natural ambient light. It is possible that iodine is converted into an inorganic form, which can be assessed using inversion voltammetry [27]. Consequently, the storage of embolizing formulations with iohexol should be conducted in a dark environment, avoiding exposure to light.

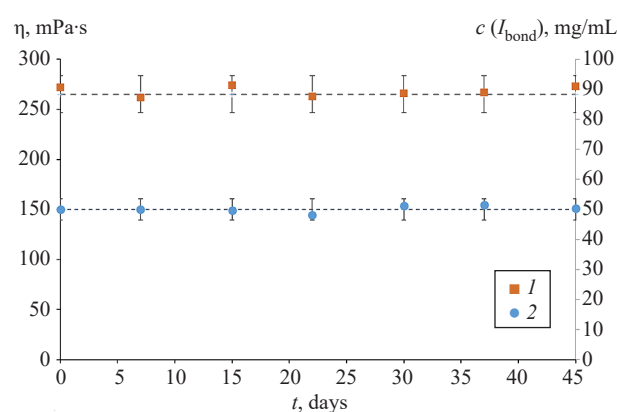


Fig. 2. Dependencies of the dynamic viscosity coefficient η (1) and the content of bound iodine c (2) on exposure duration

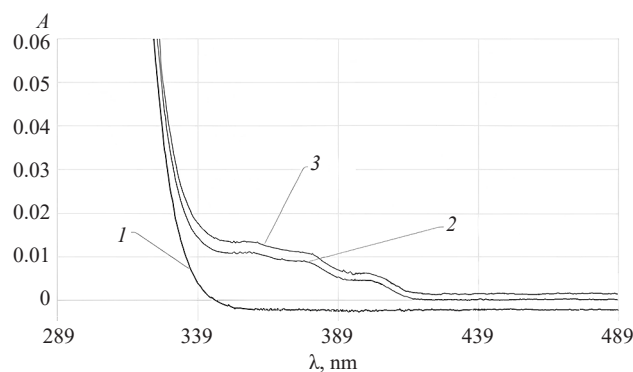


Fig. 3. Typical UV-visible spectra of iohexol solution in dimethyl sulfoxide under storage in the light for 0 (1), 6 (2), and 24 days (3)

At the second stage of the work, we obtained solid emboli from polymer solutions in water and investigated their stability during long-term exposure to an aquatic environment. The differential curves of the molecular weight distribution calculated on the basis of chromatograms are shown in Fig. 4.

¹ GPM 1.1.0009.15. Expiration dates of medicines. The State Pharmacopoeia of the Russian Federation, 13th edition (SP RF XIII). URL: <https://pharmacopoeia.regmed.ru/pharmacopoeia/izdanie-13/1/1-1-1-9/sroki-godnosti-lekarstvennykh-sredstv/>. Accessed September 24, 2025. (In Russ.).

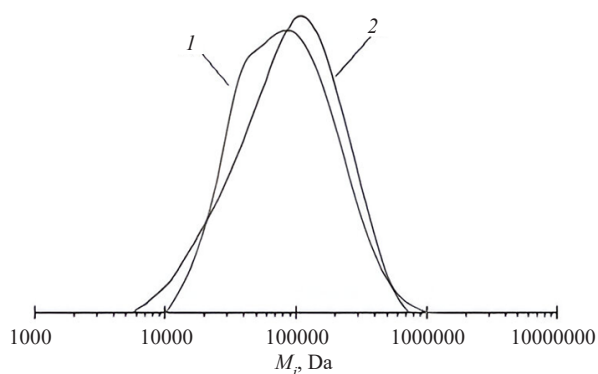


Fig. 4. Characteristic differential molecular weight distribution curves M_i for the original polymer (1) and the polymer aged in water for eight years (2)

All the distributions obtained are monomodal, which makes it possible to calculate the values of the number-average molecular weight M_n and weight-average molecular weight M_w , as well as the ratio M_w/M_n (Table 2). Figure 4 and Table 2 show that the molecular weight distributions are almost identical, with the average molecular weights and polydispersity coefficients M_w/M_n being close. This finding indicates a negligible degradation of cellulose diacetate in the aquatic environment over a period of eight years

Furthermore, we employed the GC–MS method to analyze the aqueous medium from samples of the same emboli. A typical GC–MS chromatogram is shown

in Fig. 5; the analysis of the results using the NIST² GC–MS database revealed the presence of 2-pentanone (degree of coincidence 98.0%), dimethyl sulfone (degree of coincidence 92.8%), and glycerin (degree of coincidence 91.2%) in the sample. At the same time, the expected degradation products of the polysaccharide chain were absent. It can be argued with a certain degree of confidence that 2-pentanone and glycerin can be considered as products of thermal degradation of polyethylene glycol, a modifier of cellulose diacetate, and dimethyl sulfone as a product of the transformation of a solvent, dimethyl sulfoxide, from which emboli are formed.

A significant increase in storage time does not lead to fundamental changes in the observed pattern. Thus, it appears safe to conclude that cellulose diacetate exhibits long-term stability (for at least eight years) when exposed to an aqueous medium.

CONCLUSIONS

Our study has addressed the stability of cellulose diacetate and iohexol solutions in dimethyl sulfoxide, which are utilized as liquid embolizing agents. It is shown that these solutions, when stored in the dark, do not change their rheoviscometric characteristics and the content of bound iodine for at least 45 days at 60°C, which corresponds to three years of storage

Table 2. Molecular weight characteristics of the initial polymer and the polymer aged in water for eight years

Sample	M_n^* , kDa	M_w^* , kDa	M_w/M_n^*
Initial polymer	59.5	116.4	1.96
Polymer stored in water for eight years	57.5	124.8	2.17

* Determined from the gel permeation chromatography data.

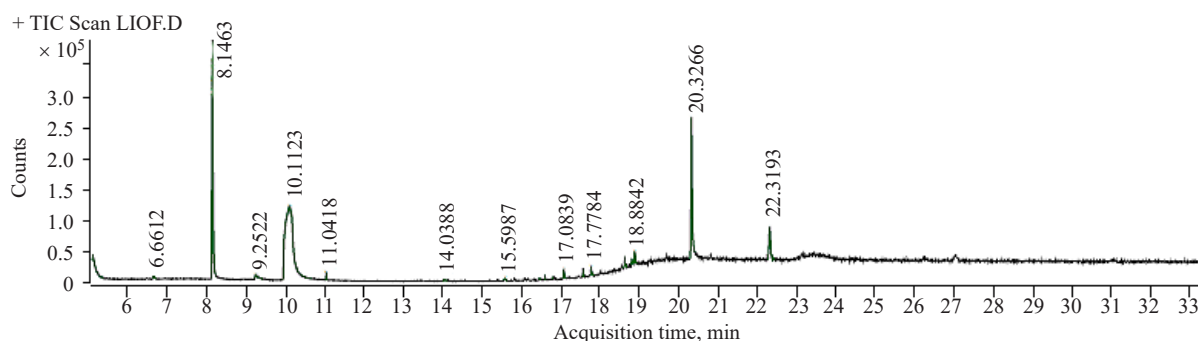


Fig. 5. Characteristic GC–MS chromatogram for a solution of lyophilized aqueous extract from a solid embolus

² NIST Chemistry WebBook. URL: <https://webbook.nist.gov/chemistry>. Accessed September 22, 2025.

under natural conditions. It is demonstrated that the contact of the solution with an inert gas (argon) or air during storage does not fundamentally affect these results. However, in order to avoid yellowing of the composition, it is recommended that the solution be stored in the dark.

The long-term study of the behavior of solid polymer emboli in contact with an aqueous medium has demonstrated that the molecular weight characteristics of the polymer and the composition of the filler fluid remain constant over an eight-year period. This observation suggests the utilization of such emboli as products of prolonged contact with the patient's body (category C).

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Authors' contributions

D.V. Nebesnaia—planning and conducting experimental research, processing the obtained data and discussing the results, preparing the texts of the article.

E.S. Terendiak—planning and conducting experimental research, processing the obtained data and discussing the results, preparing the text of the article.

O.A. Legon'kova—consulting on individual stages of the research, scientific editing of the work.

S.A. Kedik—research concept, scientific editing of the work.

A.V. Panov—consulting at various stages of the research, scientific editing of the work.

E.S. Zhavoronok—research concept and planning, discussion and analysis of the results, preparing the text of the article.

The authors declare no conflicts of interest.

REFERENCES

1. Dan V.N. *Angiodisplazii (vrozhdennyye poroki razvitiya sosudov) (Angiodysplasia (Congenital Vascular Malformations))*. Moscow: Verdana; 2008, 200 p. (In Russ.). ISBN 978-5-901439-30-2
2. Chabrot P., Boyer L. *Embolization*. Springer; 2014, 453 p. <https://doi.org/10.1007/978-1-4471-5182-1>
3. Varghese K., Adhyapak S. *Therapeutic Embolization*. Springer; 2017, 133 p. <https://doi.org/10.1007/978-3-319-42494-1>
4. Goode J.A., Matson M.B. Embolisation of cancer: what is the evidence? *Cancer Imaging*. 2004;4(2):133–141. <https://doi.org/10.1102/1470-7330.2004.0021>
5. Alluhaybi A.A., Abdulqader S.B., Altuhayni K., AlTurkstani A., Kabbani A., Ahmad M. Preoperative trans-arterial embolization of a giant scalp congenial hemangioma associated with cardiac failure in a premature newborn. *J. Int. Med. Res*. 2020;48(12):1–7. <https://doi.org/10.1177/0300060520977589>
6. Potts M.B., Zumofen D.W., Raz E., Nelson P.K., Riina H.A. Curing arteriovenous malformations using embolization. *Neurosurg. Focus*. 2014;37(3):E19. <https://doi.org/10.3171/2014.6.FOCUS14228>
7. Orron D.E., Bloom A.I., Neeman Z. The role of transcatheter arterial embolization in the management of nonvariceal upper gastrointestinal bleeding. *Gastrointest. Endosc. Clin. North Am*. 2018;28(3):331–349. <https://doi.org/10.1016/j.giec.2018.02.006>
8. Dan V.N., Sapelkin S.V., Legon'kova O.A., Tsygankov V.N., Varava A.B., Kedik S.A., Zhavoronok E.S., Panov A.V. Materials and methods of arteriovenous malformations endovascular treatment: opportunities and problems. *Voprosy biologicheskoi, meditsinskoi i farmatsevticheskoi khimii = Problems of Biological, Medical and Pharmaceutical Chemistry*. 2016;19(7):3–11 (in Russ.). <https://www.elibrary.ru/whpuev>

СПИСОК ЛИТЕРАТУРЫ

1. Дан В.Н. *Ангиодисплазии (врожденные пороки развития сосудов)*. М.: Вердана; 2008, 200 с. ISBN 978-5-901439-30-2
2. Chabrot P., Boyer L. *Embolization*. Springer; 2014, 453 p. <https://doi.org/10.1007/978-1-4471-5182-1>
3. Varghese K., Adhyapak S. *Therapeutic Embolization*. Springer; 2017, 133 p. <https://doi.org/10.1007/978-3-319-42494-1>
4. Goode J.A., Matson M.B. Embolisation of cancer: what is the evidence? *Cancer Imaging*. 2004;4(2):133–141. <https://doi.org/10.1102/1470-7330.2004.0021>
5. Alluhaybi A.A., Abdulqader S.B., Altuhayni K., AlTurkstani A., Kabbani A., Ahmad M. Preoperative trans-arterial embolization of a giant scalp congenial hemangioma associated with cardiac failure in a premature newborn. *J. Int. Med. Res*. 2020;48(12):1–7. <https://doi.org/10.1177/0300060520977589>
6. Potts M.B., Zumofen D.W., Raz E., Nelson P.K., Riina H.A. Curing arteriovenous malformations using embolization. *Neurosurg. Focus*. 2014;37(3):E19. <https://doi.org/10.3171/2014.6.FOCUS14228>
7. Orron D.E., Bloom A.I., Neeman Z. The role of transcatheter arterial embolization in the management of nonvariceal upper gastrointestinal bleeding. *Gastrointest. Endosc. Clin. North Am*. 2018;28(3):331–349. <https://doi.org/10.1016/j.giec.2018.02.006>
8. Дан В.Н., Сапелкин С.В., Легонькова О.А., Цыганков В.Н., Варава А.Б., Кедик С.А., Жаворонок Е.С., Панов А.В. Материалы и методы эндоваскулярного лечения артериовенозных мальформаций: возможности и проблемы. *Вопросы биологической, медицинской и фармацевтической химии*. 2016;19(7):3–11. <https://www.elibrary.ru/whpuev>
9. Guimaraes M., Lencioni R., Gary P. *Embolization Therapy: Principles and Clinical Applications*. Wolters Kluwer Health; 2014, 816 p.

9. Guimaraes M., Lencioni R., Gary P. *Embolization Therapy: Principles and Clinical Applications*. Wolters Kluwer Health; 2014, 816 p.
10. Hoshino J., Ubara Y., Suwabe T., Sumida K., Hayami N., Mise K., Hiramatsu R., Hasegawa E., Yamanouchi M., Sawa N., Takei R., Takaichi K. Intravascular embolization therapy in patients with enlarged polycystic liver. *Am. J. Kidney Dis.* 2014;63(6):937–944. <https://doi.org/10.1053/j.ajkd.2014.01.422>
11. Reshetnyak D.V., Zhavoronok E.S., Legon'kova O.A., *et al.* Modern Liquid Embolization Agents Based on Polymers: Composition, Characteristics, and Areas of Application. Review. *Polym. Sci. Ser. D.* 2022;15(1):64–70. <https://doi.org/10.1134/S1995421222010154> [Original Russian Text: Reshetnyak D.V., Zhavoronok E.S., Legon'kova O.A., Ogannisyana A.S., Panov A.V., Kedik S.A. Modern liquid embolizing agents based on polymers: composition, properties and application (Review). *Vse materialy. Ehntsiklopedicheskii spravochnik.* 2021;6:3–13 (in Russ.). <https://doi.org/10.31044/1994-6260-2021-0-6-3-13>]
12. Legon'kova O.A., Dan V.N., Sapelkin S.V., *et al.* Regularities of formation of emboli of liquid polymer solutions in aqueous medium. *Polym. Sci. Ser. D.* 2017;10(1):68–73 (in Russ.). <https://doi.org/10.1134/S1995421217010154> [Original Russian Text: Legon'kova O.A., Dan V.N., Sapelkin S.V., Kedik S.A., Zhavoronok E.S., Panov A.V., Asanova L.Yu., Ogarkova P.L., Shilov M.S. Regularities of formation of emboli of liquid polymer solutions in aqueous medium. *Vse materialy. Ehntsiklopedicheskii spravochnik.* 2016;6:9–15 (in Russ.). <https://www.elibrary.ru/wfnipv>]
13. Legon'kova O.A., Stafford V.V., Ogannisyana A.S., Panov A.V., Zhavoronok E.S., Kedik S.A., Pozyabin S.V., Chupin A.V., Sapelkin S.V., Alekyan B.G. Safety and efficacy assessment of cellulose acetate in modeling of rabbit femoral artery embolization. *Ehndovaskulyarnaya khirurgiya = Russ. J. Endovascular Surgery.* 2021;8(4):398–411 (in Russ.). <https://doi.org/10.24183/2409-4080-2021-8-4-398-411>
14. Legon'kova O.A., Stafford V.V., Ogannisyana A.S., Zhavoronok E.S., Panov A.V., Vinokurova T.I., Kedik S.A. Influence of the nature of radiopaque substances on the behavior of embolizing systems *in vivo*. *Biotechnologiya = Biotechnology.* 2022;38(3):62–69 (in Russ.). <https://doi.org/10.56304/S0234275822030048>
15. Tokunaga K., Kinugasa K., Meguro T., Sugiu K., Nakashima H., Mandai Sh., Ohmoto T. Curative treatment of cerebral arteriovenous malformations by embolisation using cellulose acetate polymer followed by surgical resection. *Journal of Clinical Neuroscience.* 2000;7(Suppl. A):1–5. <https://doi.org/10.1054/jocn.2000.0700>
16. Wright K.C., Greff R.J., Price R.E. Experimental evaluation of cellulose acetate NF and ethylene-vinyl alcohol copolymer for selective arterial embolization. *J. Vascul. Int. Radiol.* 1999;10(9):1207–1218. [https://doi.org/10.1016/S1051-0443\(99\)70221-6](https://doi.org/10.1016/S1051-0443(99)70221-6)
17. Tokunaga K., Kunigasa K., Kawada S., Nakashima H., Tamiya T., Hirotsune N., Mandai Sh., Ohmoto T. Embolization of cerebral arteriovenous malformations with cellulose acetate polymer: a clinical, radiological, and histological study. *Neurosurgery.* 1999;44(5):981–989. <https://doi.org/10.1097/00006123-199905000-00026>
18. Brayton C.F. Dimethyl sulfoxide (DMSO): a review. *Cornell Veter.* 1986;76(1):61–90.
19. Madsen B.K., Hilscher M., Zetner D., Rosenberg J. Adverse reactions of dimethyl sulfoxide in humans: a systematic review. *F1000Res.* 2019;7:1746. <https://doi.org/10.12688/f1000research.16642.2>
20. Lord J., Britton H., Spain S.G., Lewis A.L. Advancements in the development on new liquid embolic agents for use in therapeutic embolization. *J. Mater. Chem. B.* 2020;8(36):8207–8218. <https://doi.org/10.1039/d0tb01576h>
21. Hu J., Albadawi H., Chong B.W., Deipolyi A.R., Sheth R.A., Khademhosseini A., Oklu R. Advances in biomaterials and technologies for vascular embolization. *Adv. Mater.* 2019;31(33):e1901071. <https://doi.org/10.1002/adma.201901071>
22. Tian L., Lu L., Feng J., Melancon M.P. Radiopaque nano and polymeric materials for atherosclerosis imaging, embolization and other catheterization procedures. *Acta Pharm. Sinica B.* 2018;8(3):360–370. <https://doi.org/10.1016/j.apsb.2018.03.002>

20. Lord J., Britton H., Spain S.G., Lewis A.L. Advancements in the development on new liquid embolic agents for use in therapeutic embolization. *J. Mater. Chem. B.* 2020;8(36): 8207–8218. <https://doi.org/10.1039/d0tb01576h>
21. Hu J., Albadawi H., Chong B.W., Deipolyi A.R., Sheth R.A., Khademhosseini A., Oklu R. Advances in biomaterials and technologies for vascular embolization. *Adv. Mater.* 2019;31(33):e1901071. <https://doi.org/10.1002/adma.201901071>
22. Tian L., Lu L., Feng J., Melancon M.P. Radiopaque nano and polymeric materials for atherosclerosis imaging, embolization and other catheterization procedures. *Acta Pharm. Sinica B.* 2018;8(3):360–370. <https://doi.org/10.1016/j.apsb.2018.03.002>
23. Reshetnyak D.V., Zhavoronok E.S., Legon'kova O.A., *et al.* A Spectrophotometric Study of the Interaction of Aromatic and Aliphatic Iodine-Containing Substances with Dimethyl Sulphoxide. *Polym. Sci. Ser. D.* 2022;15(4):543–548. <https://doi.org/10.1134/s1995421222040232> [Original Russian Text: Reshetnyak D.V., Zhavoronok E.S., Legon'kova O.A., Ogannisyan A.S., Panov A.V., Kedik S.A. A Spectrophotometric Study of the Interaction of Aromatic and Aliphatic Iodine-Containing Substances with Dimethyl Sulphoxide. *Klei. Germetiki. Tekhnologii = Adhesives. Sealants. Technologies.* 2022;5:25–31(in Russ.). <https://doi.org/10.31044/1813-7008-2022-0-5-25-31>]
24. Klyubin V.V., Klyubina K.A., Makovetskaya K.N. A Spectroscopic Method for Determining Free Iodine in Iodinated Fatty-Acid Esters. *Opt. Spectrosc.* 2018;124(1): 53–56. <https://doi.org/10.1134/S0030400X18010101> [Original Russian Text: Klyubin V.V., Klyubina K.A., Makovetskaya K.N. A Spectroscopic Method for Determining Free Iodine in Iodinated Fatty-Acid Esters. *Optika i spektroskopiya.* 2018;124(1):56–59 (in Russ.). <http://doi.org/10.21883/OS.2018.01.45357.135-17>]
25. Giordano M.C., Bazán J.C., Arvia A.J. The interaction of iodine with dimethylsulphoxide in carbon tetrachloride solutions. *J. Inorg. Nuclear Chem.* 1966;28(5):1209–1214. [https://doi.org/10.1016/0022-1902\(66\)80447-5](https://doi.org/10.1016/0022-1902(66)80447-5)
26. Thomsen H.S., Bellin M.-F., Jakobsen Ja.A., Webb Ju.A.W. Contrast media classification and terminology. In: Thomsen H., Webb Ju. (Eds.). *Contrast Media. Safety Issues and ESUR Guidelines.* Berlin, Heidelberg: Springer-Verlag; 2014. P. 3–11. https://doi.org/10.1007/174_2013_864
27. Nikulin A.V., Martynov L.Yu., Gabaeva R.S., Lazov M.A. Development of a new inversion-voltammetric technique in determining inorganic iodine in *Laminariae thalli* L. for the quality control of raw materials in factory laboratories. *Tonk. Khim. Tekhnol. = Fine Chem. Technol.* 2024;19(4):372–383. <https://doi.org/10.32362/2410-6593-2024-19-4-372-383>
23. Решетняк Д.В., Жаворонок Е.С., Легонькова О.А., Оганисян А.С., Панов А.В., Кедик С.А. Спектрофотометрическое исследование взаимодействия ароматических и алифатических йодсодержащих веществ с диметилсульфоксидом. *Клей. Герметики. Технологии.* 2022;5:25–31. <https://doi.org/10.31044/1813-7008-2022-0-5-25-31>
24. Клюбин В.В., Клубина К.А., Маковецкая К.Н. Спектротометрический метод определения несвязанного йода в йодированных эфирах жирных кислот. *Оптика и спектроскопия.* 2018;124(1):56–59. <http://dx.doi.org/10.21883/OS.2018.01.45357.135-17>
25. Giordano M.C., Bazán J.C., Arvia A.J. The interaction of iodine with dimethylsulphoxide in carbon tetrachloride solutions. *J. Inorg. Nuclear Chem.* 1966;28(5):1209–1214. [https://doi.org/10.1016/0022-1902\(66\)80447-5](https://doi.org/10.1016/0022-1902(66)80447-5)
26. Thomsen H.S., Bellin M.-F., Jakobsen Ja.A., Webb Ju.A.W. Contrast media classification and terminology. In: Thomsen H., Webb Ju. (Eds.). *Contrast Media. Safety Issues and ESUR Guidelines.* Berlin, Heidelberg: Springer-Verlag; 2014. P. 3–11. https://doi.org/10.1007/174_2013_864
27. Никулин А.В., Мартынов Л.Ю., Габаева Р.С., Лазов М.А. Разработка новой инверсионно-вольтамперометрической методики определения неорганического йода в слоевищах ламинарии (*Laminariae thalli* L.) для контроля качества сырья в условиях заводских лабораторий. *Тонкие химические технологии.* 2024;19(4):372–383. <https://doi.org/10.32362/2410-6593-2024-19-4-372-383>

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