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Investigation of physical and chemical parameters of the raw hydrocarbon material base of the Kaliningrad region for the concept development of an oil refinery

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Abstract

The article analyzes the factors that determine the necessity of oil refinery construction in the Kaliningrad region of the Russian Federation. The assessment of the existing and prospective raw material base is performed. The data for the development of the feasibility study for an oil refinery construction are formed and analyzed. Taking into account the outdated data on the parameters of hydrocarbon raw materials produced in the region, as well as significant changes in the raw material base due to the tendency to develop offshore, rather than continental, fields the physical and chemical parameters of the oil fields of the Kaliningrad region are investigated for the possibility of their further use in oil refining in order to obtain high-quality gasoline and diesel fuel. The laboratory studies of oil samples on viscosity, density, fractional composition, content of sulfur, chloride salts, mechanical impurities, water, and flash point determination are carried out on the basis of the Russian state standards. The different variants of the refinery layouts are analyzed, considering the available raw material base. Taking into account the initial data obtained, a preliminary predesign study of the technological scheme and the refinery mass balance is carried out and presented in the article.

Keywords

oil quality
fractional composition
refinery design
regional energy security
physical and chemical oil analysis

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Key findings

- According to the results of physical and chemical studies, the oils of the Kaliningrad region offshore fields (including new deposit D33) can be classified as the first-class oil with a low sulfur and other impurities content along with high concentrations of light fractions.
- The necessities of the Kaliningrad region in gasoline, diesel, fuel oil, and other petroleum products could be fulfilled by local crude oil fields. The volume and quality of this crude oils from local fields correspond technical requirements for classic refinery process.
- The optimal scheme of a refinery plant for the Kaliningrad region should use fuel variant of the processing. The final volume of products in this scheme will be around 220 thousand tons of gasoline, 120 thousand tons of kerosene and 250 thousand tons of diesel fuel annually.

1. Introduction

In 2023–2024, the new offshore field of oil D33 is planned to be put into the operation in the Kaliningrad region, with a recoverable reserve volume of about 20 million tons [1]. Considering the fields currently in the operation, annual oil production volumes should exceed 2 million tons. Besides the D33 oil field, there are prospects for the development of two more offshore structures: D6 Yuzhnaya and D29 [2, 3].

Thus, annual oil production volumes exceeding 1 million tons will remain the same in the Kaliningrad Region in the next 15–20 years, which provides the necessary raw material base for the creation of an oil refinery. At the same time, the consumption of gasoline and diesel fuel is constantly growing in the region. For instance, in 2021 the Kaliningrad region consumed various brand gasoline in the amount of 243,760 thousand tons, which is 22% more than in 2011. As for diesel fuel, the Kaliningrad region consumed 200,300 thousand tons of it in 2021, which is 34% more than in 2011 (Figure 1) [4].

As the result, the volume of hydrocarbon consumption is steadily growing in the region, while the existing oil production capacities and the quality of the recoverable raw materials can meet these needs [4]. Despite having its own resource base, diesel fuel and gasoline are imported to the region from the main territory of the Russian Federation due to the lack of specialized petrochemical enterprises [5].

Calculations show that the cost of transporting a 60-ton tank from the Nizhny Novgorod refinery to Kaliningrad, provided that it is owned, is 174,276 rubles without VAT, to this the fee of 10% is added on the territory of Belarus and Lithuania, which is 3,972 rubles and 5,659 rubles respectively [6]. As a result, transportation costs for the delivery of gasoline and diesel fuel to the region by rail in 2021 amounted to 1,696,402,584 rubles without VAT and freight forwarders' fees [7]. Based on the presented geological and economic indicators, as well as the current geopolitical situation, providing the Kaliningrad region with its own oil refining products is promising and a priority [6]. As the result, the purpose of this study is to conduct a pre-project assessment of the resource base of the region based on physical and chemical characteristics of hydrocarbon raw materials and the choice of the new oil refinery layout concept.

2. The experimental part

To determine physical and chemical characteristics of the hydrocarbon raw material base of the Kaliningrad region, a number of technological samples were selected, in terms of the largest deposits of the region on the land - Ladushkinskoye, Krasnoborskoye, and on the shelf – D6 and D33 [2]. The samples were analyzed according to the main physical and chemical parameters for the study and understanding of their properties in terms of further refining and a relevant economic model forecasting of the projected refinery. In order to determine the fractional composition, the tests were carried out according to [8]. According to the experimental data, true boiling point curves were constructed and comparative diagrams were compiled (Figure 2a, 2b). As the result, we can assume that the following fractions predominate in the oil samples of the largest deposits of the Kaliningrad region: diesel and fuel oil.

However, the total share of light petroleum products is more than 45.0% by weight, which makes it possible to attribute these oils to type T1 according to the technological classification of oils and along with a density value – to type 0 (especially light) according to the technical classification of GOST R 51858-2002. This creates excellent opportunities for the production of the most valuable commodity petroleum products [9].

The highest content of light fractions is found in the oil of the Krasnoborsky continental deposit and the offshore deposit D6.

When determining the density, tests were carried out according to GOST R 51069-97, while GOST 33-2016 was used to determine the kinematic viscosity.

As the result, it was found that all the studied oil samples of the Kaliningrad region deposits belong to type 0 (especially light) according to GOST R 51858-2002. Such oils are characterized in general by the predominance of methane hydrocarbons, a low content of resinous-asphaltene components, and in fractional terms – by a high content of gasoline and kerosene fractions [10].

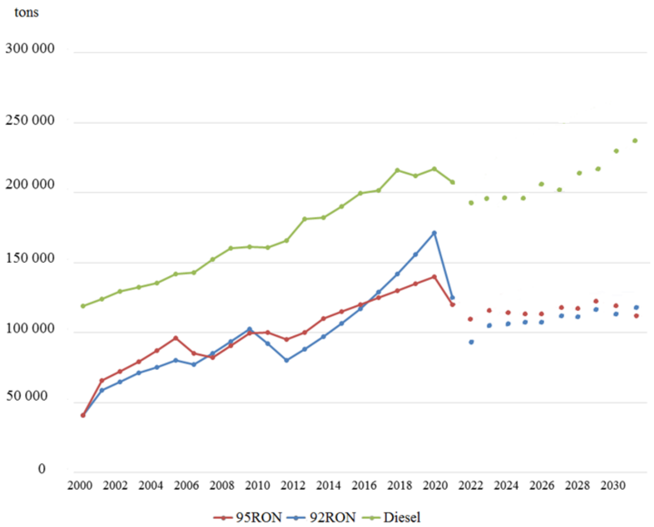

Figure 1 Volumes of gasoline and diesel fuel consumption in the Kaliningrad region in 2000–2030.

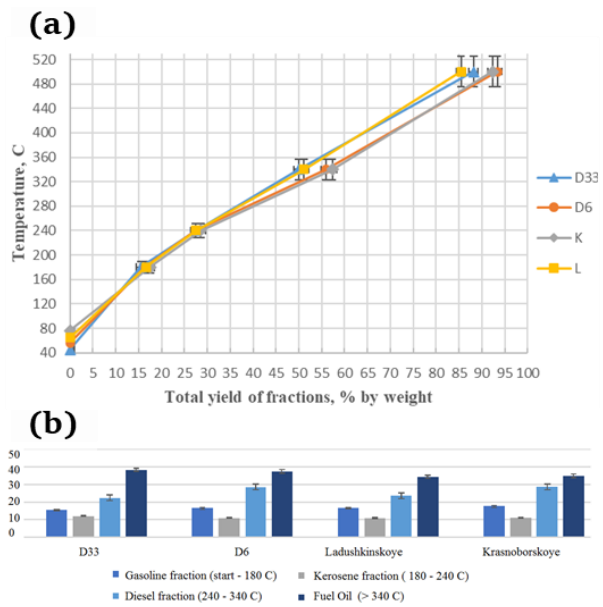

Figure 2 True boiling point curves of the studied deposit samples (a), comparison of percent content by weight (b).

Table 1 shows the values of experimentally determined kinematic viscosity, as well as the values of dynamic viscosity obtained from multiplying by the previously determined density values. Refining light oil requires less economic costs; that is why it is considered especially valuable.

The constant of the used capillary viscometer type – VPJ-1 is 0.1068 mm^2/s^2. According to the data obtained, it can be concluded that all types of tested oils belong to the category with insignificant viscosity (<5 mPa·s) [11]. The flash point and ignition temperature in an open crucible were determined in accordance with GOST 4333-2014. To determine the ignition temperature, after performing the flash detection procedure, the sample continued to be heated. The use of the ignition source was repeated at intervals of 2 °C until the sample's vapors ignited and burned steadily for at least 5 seconds [12]. The temperature, which was registered at this moment, was recorded as the observed ignition temperature of the sample. Then the final values of temperature were found after the adjustment procedure to the normal atmospheric pressure, according to the following empirical formula, discovered by D. Holde and K. Lohmann [13]:

$$t_{760} = t_p + 0.00012(760 - P)(273 + t_p), \quad (1)$$

where t_{760} is the flash point at normal pressure of 760 mm Hg, P – the observed pressure in units of mm Hg, t_p – the observed flash point.

As a result, it was found that all the studied oil samples of the Kaliningrad region deposits can be classified as highly flammable liquids, since their flash point is no more than 66 °C in an open crucible, which is due to their relatively low density. These samples require special precautions, especially for the oil of the Krasnoborskoye field, which is classified as a particularly dangerous highly flammable liquid (<28 °C).

Obtaining data on mechanical impurities in the studied oil samples of the Kaliningrad region deposits was carried out by conducting tests according to [14]. The sulfur content was determined according to GOST R 51947 by means of energy dispersive X-ray fluorescence spectrometry in the Laboratory of Geochemistry and reservoir oils of JSC TomskNIPIneft.

Based on the results of the mechanical impurities determination, it can be concluded that the oils comply with the requirements of GOST R 51858-2002, since the content does not exceed 0.05% [15]. It can be deduced that according to the technical classification of GOST R 51858-2002, the studied oils belong to the low-sulfur class (≤0.6% by weight) [16]. According to the technological classification, the studied oils also belong to the 1st class of low-sulfur oils (≤0.5% by weight). The content of chloride salts in the samples was determined according to GOST 21534 by method B – non-aqueous potentiometric titration in the Laboratory of Geochemistry and reservoir oils of JSC TomskNIPIneft.

Based on the results of determining the water and chloride salts content, it can be concluded that according to GOST R 51858-2002, the studied oils belong to group 1 based on the extent of preparation, since the water content does not exceed 0.5%, while the chloride salt content does not exceed 100 mg/dm^3 [17].

The octane numbers of gasoline fractions (initial boiling point – 180 °C) of the studied samples of oil and commercial brands of gasoline of 92 and 95 RON as comparison samples were determined using the quality portable octane meter, type – SIM-3B, which belongs to the group of automated analyzers according to GOST 16851-71, where sampling is done manually, and the measurement of the octane number occurs automatically [18, 19]. The principle of operation of the analyzer is based on the measurement of the dielectric constant of leaded and unleaded motor gasolines, which is functionally dependent on the octane number, and the transfer of the octane number from standard samples of gasoline to the tested samples of gasoline.

As a result of determining the octane numbers, it can be concluded that the straight-run gasoline fractions of the studied oils are a good enough base for further compounding and obtaining commercial automobile gasoline by adding various high-octane components and additives, primarily, reformat [20].

Table 1 Density (at 15 °C), kinematic and dynamic viscosity (at 60 °C) of oil samples.

Oilfield	Density, kg/m³	Kinematic viscosity mm²/s (cSt)	Dynamic viscosity mPa·s
Ladush-	823.2±0.5	0.497±0.021	0.409±0.021
Krasnobor-	825.7±0.5	0.472±0.013	0.390±0.013
D6	823.2±0,5	0.505±0.018	0.416±0.018
D33	824.2±0.5	0.428±0.011	0.353±0.011

Table 2 Density (at 15 °C), kinematic and dynamic viscosity (at 60 °C) of oil samples.

Oilfield	Average value of flash temperature, °C	Flash point adjusted for normal pressure, °C	Average value of ignition temperature, °C	Ignition temperature adjusted for pressure, °C
Ladushkinskoye	54.5±0.5	54.8±0.5	57.0±0.5	57.3±0.5
Krasnoborskoye	15.5±0.5	15.8±0.5	17.0±0.5	17.3±0.5
D6	62.0±0.5	62.3±0.5	63.0±0.5	63.3±0.5
D33	45.5±0.5	45.8±0.5	47.5±0.5	47.8±0.5

Table 3 Results of mechanical impurities and sulfur determination in oil samples.

Oilfield	Percentage of mechanical impurities, %	Sulfur mass fraction, %
Ladushkinskoye	0.032±0.002	0.127±0.011
Krasnoborskoye	0.031±0.006	0.11±0.06
D6	0.038±0.006	0.127±0.013
D33	0.031±0.009	0.127±0.006

Table 4 The content of chloride salts and water in oil samples.

Oilfield	Concentration, mg/l	Percentage of water, %
Ladushkinskoye	5.54±0.27	0.056±0.013
Krasnoborskoye	<5.00	0.176±0.011
D6	5.25±0.25	0.058±0.007
D33	<5.00	0.060±0.006

Table 5 Octane values according to research and motor methods for the gasoline fraction of the studied oil samples (initial boiling point –180 °C) and commercial brands of gasoline 92 and 95 RON.

Oilfield	MON (5)	RON (8)
Ladushkinskoye	68.0±0.9	77.3±1.0
Krasnoborskoye	71.7±0.9	79.2±1.1
D6	69.02±0.18	78.4±0.5
D33	70.6±1.0	78.0±0.6
92 RON	83.0±0.8	92.02±0.28
95 RON	86.20±0.78	95.8±0.5

3. Results and Discussion

Summing up all the studies of the physical and chemical properties of oil samples, it can be concluded that according to the technical classification of GOST R 51858-2002, the studied oils belong to class 1 (low-sulfur); type 0 (especially light); group 1 (according to the extent of feedstock preparation). The designation of the studied oils according to the standard is "Oil 1.0.1 GOST R 51858-2002". This makes them very useful, allowing a large number of valuable products from gasoline to diesel fuel and heavier products to be obtained at relatively low cost.

According to the technological classification, the studied oils belong to class 1 (low-sulfur) and the first type (T1) in terms of the yield of light fractions.

Thus, it was found from the conducted physical and chemical studies of oil samples from the Kaliningrad region deposits that oils from all major deposits can be used to produce gasoline, kerosene and diesel fuel, since their properties are low viscosity, low content of mechanical impurities and a high proportion of light fractions [21]. At the same time, these characteristics are more apparent in the oil of offshore fields that creates the necessary raw material base, taking into account the tendency to their development. The preliminary material balance to ensure the needs of the Kaliningrad region with petroleum products obtained from local oil fields is given according to the average oil indicators of the Kaliningrad fields based on the experimental data of the fractional composition in Table 6. The balance is based on the distillation (primary) processes and not takes into account the additional separation of fuel oil (secondary processes).

From the given table it can be concluded that there is a sufficiently large excess of kerosene, diesel and especially boiler fuel as a result of oil refining based only on the primary processes with further refinement of the resulting products. It is advisable to sell these surplus products to other regions of Russia, transporting, for example, by sea, while almost the entire volume of gasoline produced is consumed within the region.

Taking into account the obtained physical and chemical data on the studied oils, as well as the needs of the region for petroleum products, the following economic concepts of designing an oil refinery were considered, given in order of increasing the oil refining efficiency.

The first concept deals with a primary crude oil processing, i.e., oil distillation of the entire volume. A certain amount of crude oil is distilled only for the needs of the region, the rest volume is sent for sale in its original state.

The second concept lies within a deep processing of crude oil only for the needs of the region. With this option a certain amount of oil is processed using secondary or destructive processes (cracking, reforming, etc.) for the needs of the region, while the rest of the crude oil volume is sold as a raw material.

The third concept lies in a deep processing of some crude oil volume only for the needs of the region, while the rest volume of oil is processed to the form of primary or semi-finished products (straight-run gasoline, etc.) and sent for sale.

The fourth concept is a deep processing of the entire volume of crude oil, including for export, i.e., by means of distillation and the above-mentioned secondary or destructive processes. In this variant one part of the products volume is sold within the region, and the other part of products is sold to other regions.

The main classical technological pathways of oil refining were also considered: simple fuel, deep fuel, fuel-oil and petrochemical (complex). A rationale for the greatest expediency of the third economic concept, which consists of partially deep oil processing only for the region needs, while other volume of oil is sent in the form of primary products and semi-finished products for sale, was made as a result.

It corresponds to a simple fuel variant of oil processing for the projected oil refinery in terms of chemical technology, which implies a small number of technological processes and the production of a small assortment of commodities: 55–60% of which are motor fuels (gasoline, kerosene, diesel fuel), and 30–35% are boiler fuels [22]. That means that vacuum fuel oil separation columns and such processes as catalytic cracking, thermal cracking, hydrocracking, etc. are not provided.

Table 6 The material balance of the fraction output according to the average composition of the Kaliningrad region oil.

Oil fractions	Average yield by fractions, % by weight	TOTAL, total production, thousand tons/year	Annual average demand in thousand tons per year	Surplus for sale, thousand tons/year
Gasoline	16.53	371.93	220.00	151.92
Kerosene	11.24	252.90	120.00	132.90
Diesel	25.81	580.73	250.00	330.73
Boiler fuel	36.26	815.85	220.00	595.85
Other	10.16	228.60	0.00	228.60
TOTAL	–	2250.00	810.00	1440.00

As it is known, it is mandatory to take into account the physical and chemical properties of raw materials in a simple distillation variant of oil processing, since there is no additional opportunity to increase the oil refining efficiency due to a number of secondary (destructive) processes [23].

Considering the above mentioned facts, the proposed technological scheme for an oil refinery in the Kaliningrad region in general may look as, shown in Figure 3.

At the first stage, the oil is subjected to electric desalination and dehydration at the crude desalter unit installation, then by means of atmospheric tubing (AT) it is fractionated into gases, gasoline, kerosene, diesel fractions, and fuel oil. The gases are separated by means of gas fractionation unit with the separation of hydrogen sulfide and fuel gases, which are separated into dry and fatty gases. The gasoline fraction is fed to the secondary distillation, as a result of which two fractions of IBP –85 °C and 85–180 °C are released, being the raw materials for catalytic reforming, producing high-octane components of gasoline for compounding with a low-octane base. Kerosene and diesel fractions are subjected to hydrotreatment to obtain components of jet and diesel fuels, respectively, followed by the introduction of appropriate additives to obtain marketable products. Fuel oil is removed in a separate stream without secondary separation [23]. In view of the relatively small fuel needs of the region and the high cost of most secondary processes, primarily catalytic cracking and hydrocracking, it seems impractical to design processes to enhance oil refining efficiency by refining fuel oil. The incorporation of the catalytic reforming process to the scheme is sufficient in terms of the production of high-octane components for the gasoline production, which is the most used type of fuel in the region.

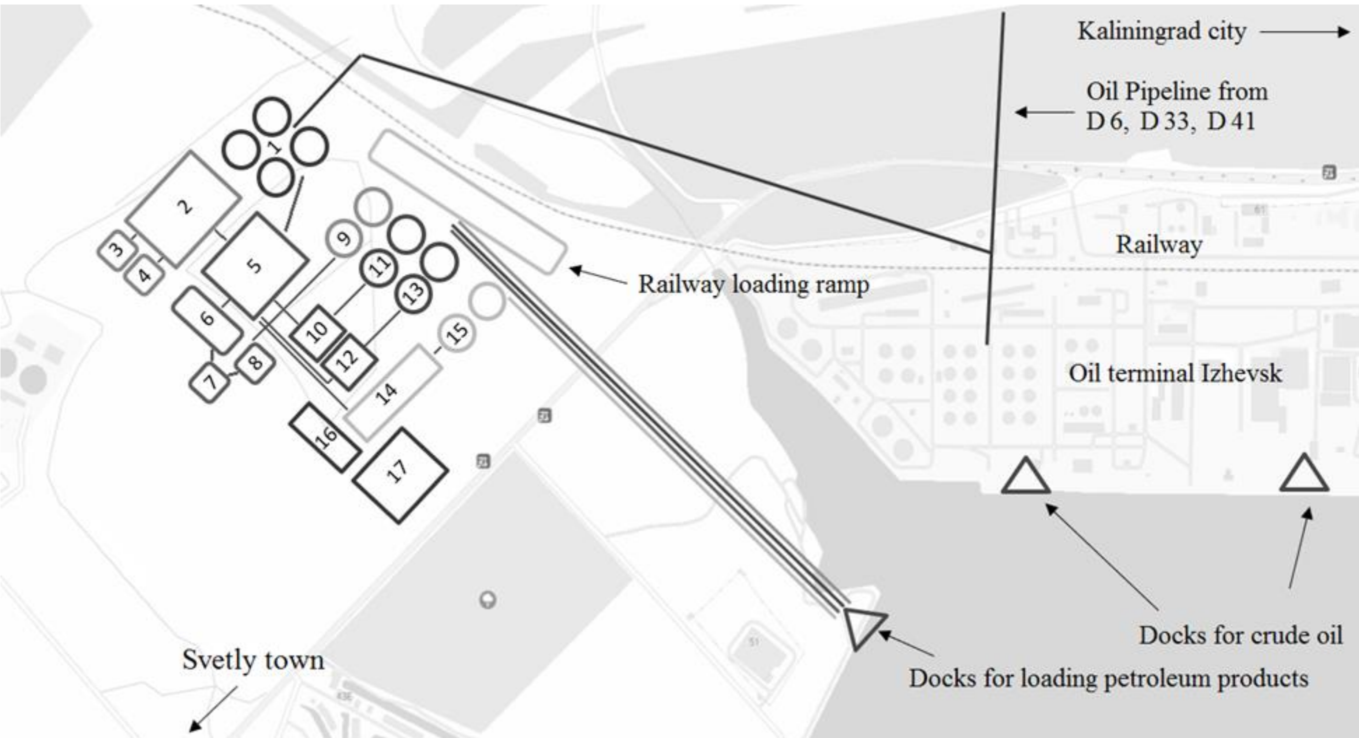

Figure 3 A variant of the Kaliningrad refinery basic plan for a "simple" oil refining scheme: 1 – Tank farm; 2 – Gas fractionation unit; 3 – Cleaning and disposal of H_2S; 4 – Fuel gas preparation unit; 5 – Atmospheric distillation (crude desalter unit and AT); 6 – Secondary distillation; 7 – Catalytic reforming; 8 – Gasoline cleaning and compounding; 9 – Petrol VST; 10 – Hydrotreating of kerosene and jet fuel; 11 – Jet fuel VST; 12 – Hydrotreating and compounding of diesel fuel; 13 – Diesel fuel VST; 14 – Fuel oil handling equipment; 15 – Fuel oil storage; 16 – Energy complex; 17 – Laboratory and administrative complex.

4. Conclusions

The conducted complex of the studies made it possible to establish the physical and chemical characteristics of hydrocarbons, currently being extracted in the Kaliningrad region and planned for the production in the next 10 years, and to clarify their parameters in terms of the organization of the crude oil processing into petroleum products.

It was determined that the oils of the Kaliningrad region, both in old deposits and in new ones, belong to class 1 (low-sulfur) and the first type (T1) in terms of the yield of light fractions according to the technological classification. In case of the technical classification of GOST R 51858-2002, the studied samples of crude oils belong to class 1 (low-sulfur); type 0 (especially light); group 1 (according to the degree of preparation).

The volume of its production in the future by 2023–2024 will be at least 2– 2.5 million tons. Gasoline consumption in the Kaliningrad Region by 2025–2027 will be about 220 thousand tons annually, diesel fuel consumption will be about 250 thousand tons annually, kerosene consumption will be about 120 thousand tons. The quality and quantity of crude oil planned for the production in the region are sufficient to organize the production of petroleum products in the Kaliningrad region. The volume of oil refining will fully satisfy the regional market for all motor and boiler fuels. Excess fuel, refined products, and crude oil unused in production can be sent to the foreign or Russian mainland market.

Based on the results obtained and taking into account the consideration of several conceptual options, it was possible to form a basic optimal option for creating an oil refinery in the region.

It seems rational to place an oil refinery on a production site next to the existing Izhevsk oil terminal, since there is a suitable transport infrastructure there. Taking into account the characteristics of raw materials and the parameters of the resulting petroleum products, it seems optimal to create an oil refinery according to the scheme of fuel variant of the processing.

Supplementary materials

No supplementary materials are available.

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Conflict of interest

The authors declare no conflict of interest.

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