DOI: https://doi.org/10.17816/DD630885

Detecting new lung cancer cases using artificial intelligence: clinical and economic evaluation of a retrospective analysis of computed tomography scans 2 years after the COVID-19 pandemic

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ABSTRACT

BACKGROUND: Chest computed tomography (CT) is the main modality used to diagnose lung lesions caused by COVID-19 infection. Since 2020, the use of this modality in the Krasnoyarsk krai has increased. However, the incidence of lung cancer decreased by 5.2%. The current situation has raised concerns about missing radiographic signs typical of lung cancer and has stimulated the search for new diagnostic modalities using artificial intelligence (AI) for data analysis.

AIM: The aim of the study was to evaluate the feasibility of using an AI algorithm to search for lung nodules based on chest CT data obtained during the COVID-19 pandemic to identify lung cancer.

MATERIALS AND METHODS: The retrospective study included chest CT scans of patients from Krasnoyarsk krai diagnosed with COVID-19 reported in the PACS base between 1 November 2020 and 28 February 2021. The interval between chest CT and AI analysis ranged from two years and one month to two years and five months. Chest-IRA algorithm was used. AI detected lung nodules with a volume greater than 100 mm^3. The radiologists divided the results into three groups based on the potential for lung cancer. The assessment of the economic benefits of using the AI algorithm considered the cost of wages and savings in the treatment of early-stage lung cancer, which affects gross regional product.

RESULTS: The AI algorithm identified nodules in 484 out of 10,500 CT scans. A total of 192 patients with a high potential for lung cancer, 103 with no signs and 60 with inconclusive signs were identified, and 112 patients with a high and moderate potential for lung cancer did not seek medical care. AI confirmed 100 (28.2%) histologically proven cases of lung cancer, with stages I–II detected in 35%.

Using AI instead of radiologists would save 25 months and 4 days of work, which is equal to 2 million 430 thousand rubles. Expected budget savings due to early detection of lung cancer vary from 10 million 600 thousand to 12 million 500 thousand rubles for each 10,500 CTs. The total economic effect for a five-year period would be from 259 million 400 thousand rubles to 305 million 100 thousand rubles.

CONCLUSION: The use of AI to evaluate chest CT scans demonstrates high performance in identifying lung nodules, including those in patients with COVID-19, confirming its potential use for early detection of incidental lung nodules that might otherwise be missed.

Keywords: lung cancer; computed tomography; artificial intelligence; chest; health economics; performance evaluation.

To cite this article:
Zukov RA, Safontsev IP, Klimenok MP, Zabrodskaya TE, Merkulova NA, Chernina VYu, Belyaev MG, Goncharov MYu, Omelyanovskiy VV, Ulianova KA, Soboleva EA, Blokhina ME, Nalivkina EA, Gombolevskiy VA. Detecting new lung cancer cases using artificial intelligence: clinical and economic evaluation of a retrospective analysis of computed tomography scans 2 years after the COVID-19 pandemic. *Digital Diagnostics.* 2024;5(4):725–739. DOI: https://doi.org/10.17816/DD630885

Received: 25.04.2024 **Accepted:** 25.08.2024 **Published online:** 05.11.2024

ECO•VECTOR

DOI: https://doi.org/10.17816/DD630885

Выявление новых случаев рака лёгкого с помощью искусственного интеллекта: клиническая и экономическая оценка ретроспективного анализа результатов компьютерной томографии через 2 года после пандемии COVID-19

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АННОТАЦИЯ

Обоснование. Компьютерная томография органов грудной клетки — основной метод диагностики изменений лёгочной ткани, вызванных инфекцией COVID-19. Так, с 2020 года в Красноярском крае увеличилась частота применения данного исследования. Тем не менее заболеваемость раком лёгкого снизилась на 5,2%. Сложившаяся ситуация вызвала опасения в отношении пропуска рентгенологических изменений, характерных для рака лёгкого, и стимулировала поиск новых диагностических методов, включая искусственный интеллект для анализа данных.

Цель — оценка возможности использования алгоритма искусственного интеллекта, направленного на поиск лёгочных узлов по данным компьютерной томографии органов грудной клетки, полученным в период пандемии COVID-19, для выявления рака лёгкого.

Материалы и методы. В ретроспективное исследование вошли результаты компьютерной томографии органов грудной клетки пациентов из Красноярского края с диагнозом COVID-19 из PACS-архива, выполненные в период с 01.11.2020 по 28.02.2021. Интервал времени между проведёнными компьютерными томографиями и применением алгоритма искусственного интеллекта составил от двух лет и одного месяца до двух лет и пяти месяцев. Использовали алгоритм искусственного интеллекта Chest-IRA. Он выявлял лёгочные узлы объёмом более 100 мм^3. Рентгенологи разделили результаты на три группы в зависимости от вероятности рака лёгкого. Оценка экономической выгоды применения алгоритма учитывала затраты на заработную плату и экономию на лечении ранних стадий рака лёгкого, влияющую на валовой региональный продукт.

Результаты. Из 10 500 результатов компьютерной томографии, алгоритм искусственного интеллекта выявил узловые образования в 484 случаях. Определены 192 пациента с высокой вероятностью рака лёгкого, 103 — без признаков и 60 — с неубедительными признаками. 112 пациентов с высокой и средней вероятностью рака лёгкого не обращались за медицинской помощью. Применение искусственного интеллекта позволило подтвердить 100 (28,2%) гистологически верифицированных случаев рака лёгкого, при этом I–II стадия выявлена в 35%.

Использование искусственного интеллекта вместо рентгенологов сэкономило бы 25 мес. и 4 дня работы — 2 430 тыс. рублей. Ожидаемая экономия бюджета в связи с выявлением рака лёгкого на ранней стадии варьирует от 10 600 тыс. до 12 500 тыс. рублей на каждые 10 500 компьютерных томографий. Общий экономический эффект за пять лет — от 259 400 тыс. до 305 100 тыс. рублей.

Заключение. Использование искусственного интеллекта для анализа результатов компьютерной томографии органов грудной клетки демонстрирует высокую эффективность в отношении выявления узловых образований лёгких, в том числе на фоне COVID-19, что подтверждает перспективы его применения для раннего обнаружения случайных лёгочных узлов, которые могли бы быть пропущены.

Ключевые слова: рак лёгкого; компьютерная томография; искусственный интеллект; грудная клетка; экономика здравоохранения; оценка эффективности.

Как цитировать:
Зуков Р.А., Сафонцев И.П., Клименок М.П., Забродская Т.Е., Меркулова Н.А., Чернина В.Ю., Беляев М.Г., Гончаров М.Ю., Омельяновский В.В., Ульянова К.А., Соболева Е.А., Блохина М.Е., Наливкина Е.А., Гомболевский В.А. Выявление новых случаев рака лёгкого с помощью искусственного интеллекта: клиническая и экономическая оценка ретроспективного анализа результатов компьютерной томографии через 2 года после пандемии COVID-19 // Digital Diagnostic. 2024. Т. 5, № 4. С. 725–739. DOI: https://doi.org/10.17816/DD630885

Рукопись получена: 25.04.2024 **Рукопись одобрена:** 25.08.2024 **Опубликована online:** 05.11.2024

DOI: https://doi.org/10.17816/DD630885

利用人工智能检测肺癌新病例：COVID-19大流行2年后计算机断层扫描结果回顾性分析的临床和经济评估

Ruslan A. Zukov[1,2], Ivan P. Safontsev[1,2], Marina P. Klimenok[2], Tatyana E. Zabrodskaya[2], Natalya A. Merkulova[2], Valeria Yu. Chernina[3], Mikhail G. Belyaev[3], Mikhail Yu. Goncharov[3,4,5], Vitaly V. Omelyanovskiy[6,7,8], Ksenia A. Ulianova[9], Evgenia A. Soboleva[3,5], Maria E. Blokhina[11], Elena A. Nalivkina[11], Victor A. Gombolevskiy[3,4,10,12]

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摘要

论证。胸腔器官计算机断层扫描是COVID-19感染引起的肺组织变化的主要诊断方法。因此，自2020年以来，这项研究在克拉斯诺亚尔斯克边疆区的应用频率有所增加。然而，肺癌的发病率却下降了5.2%。这种情况引起了人们对肺癌漏检特征性放射学变化的担忧，并促使人们寻找新的诊断技术，包括用于数据分析的人工智能（AI）。

目的 — 评估使用人工智能算法从COVID-19大流行期间获得的胸腔器官计算机断层扫描数据中，搜索肺结节发现肺癌的可行性。

材料和方法。这项回顾性研究，包括从2020年1月11日至 2021年2月28日期间，克拉斯诺亚尔斯克地区 从PACS档案中诊断为COVID-19的患者的胸腔器官计算机断层扫描结果。进行胸腔器官计算机断层扫描与应用人工智能算法之间的时间间隔从两年零一个月到两年零五个月。使用了Chest-IRA AI算法。AI检测到体积大于100㎣的肺部结节。放射科医生根据肺癌的概率将结果分为三组。使用该算法的经济效益评估，考虑到了工资成本和早期治疗肺癌所节省的费用，这些也会影响地区生产总值。

结果。在10500个计算机断层扫描结果中，人工智能算法检查出484例结节性肿块。确定了192名患肺癌高概率的患者，103名无体征，60名体征根据不足。112名肺癌高概率和中概率的患者没有就医。 通过使用人工智能，100例（28.2%）经组织学验证的肺癌患者得到了确诊，其中35%的患者处于I-II期。

使用人工智能代替放射科医生可以节省25个月零4 天的工作时间，也就是243万卢布。每进行10500次计算机断层扫描，因早期发现肺癌而节省的预算预计从1060万卢布到1250万卢布。五年的总经济效益为2.594亿卢布至3.051亿卢布。

结论。使用人工智能分析胸腔器官计算机断层扫描结果显示肺结节检测的高效率，包括在COVID-19的背景下，这证实其用于早期发现那些可能被遗漏的随机肺结节的前景。

关键词：肺癌；计算机断层扫描；人工智能；胸腔；卫生经济学；效能评估。

引用本文：
Zukov RA, Safontsev IP, Klimenok MP, Zabrodskaya TE, Merkulova NA, Chernina VYu, Belyaev MG, Goncharov MYu, Omelyanovskiy VV, Ulianova KA, Soboleva EA, Blokhina ME, Nalivkina EA, Gombolevskiy VA. 利用人工智能检测肺癌新病例：COVID-19大流行2年后计算机断层扫描结果回顾性分析的临床和经济评估. *Digital Diagnostics.* 2024;5(4):725–739. DOI: https://doi.org/10.17816/DD630885

收到：25.04.2024 **接受：**25.08.2024 **发布日期：**05.11.2024

BACKGROUND

Lung cancer is one of the cancers with the highest global prevalence and mortality rates. An estimated 2.2 million cases of lung cancer and 1.8 million deaths from this condition are reported each year [1]. The standardized lung cancer incidence in Russia is 20.8 cases per 100,000 population, with a 2.7% increase since 2020 [2]. Lung cancer rates across several Russian regions, notably the Krasnoyarsk Krai, are concerning. It ranks third among all malignancies reported in the Krasnoyarsk Krai, with breast and skin cancer being the most prevalent.

The number of chest computed tomography (CTs) in the Krasnoyarsk Krai has increased significantly since 2020 due to the COVID-19 pandemic (36,577 in 2019 vs. 236,234 in 2021). However, the lung cancer prevalence in this region declined by a mere 5.2% in comparison to 2019.

One potential reason is undiagnosed pulmonary nodular lesions brought on by alterations typical of COVID-19-associated pneumonia. This necessitates the search for novel diagnostic tools to enhance the effectiveness of lung cancer detection. Artificial intelligence (AI) is one such instrument that can serve as the primary component of hybrid diagnostics in lung cancer. During the first stage, the AI systems execute the initial screening of the CT findings; during the second stage, the AI-selected images are reviewed by specialist physicians to reach a final decision. Thus, in 2022, the population of Krasnoyarsk Krai participated in the pilot project “Retrospective Analysis of Chest CT Findings Using the Chest-IRA AI Algorithm by IRA-Labs.”

AIM: To evaluate the effectiveness of an AI algorithm for lung nodule detection based on chest CT findings acquired during the COVID-19 pandemic to detect lung cancer.

MATERIALS AND METHODS

Study design

This was an observational, single-center, retrospective, cross-sectional, single-arm study. The study design is illustrated in Fig. 1.

Eligibility criteria

The study sample was established based on the inclusion and exclusion criteria.

Inclusion criteria:

- Chest CT findings for patients from the Krasnoyarsk Krai PACS, both male and female;
- Chest CT performed without intravenous contrast for COVID-19, with the findings being interpreted by radiologists between November 1, 2020, and February 28, 2021;
- Age of patients >18 years;
- Chest CT scans are available in the DICOM file format.

Exclusion criteria:

- Available chest CT scans are in the non-DICOM file format;
- False-positive AI findings;
- CT slice thickness >1.5 mm;
- Incomplete chest CT findings;
- Significant motion artifacts;
- Recovery of anonymized patient data are unfeasible.

Study setting

Chest CT scans were conducted at the Krasnoyarsk Regional Clinical Oncological Dispensary (named after A.I. Kryzhanovsky).

Study duration

The study employed chest CT results collected between November 1, 2020, and February 28, 2021. The interval between chest CT and AI analysis varied from two years and one month to two years and five months. The specialists evaluated the results between December 5, 2022, and January 9, 2023.

Intervention

The Toshiba Aquilion 64, GE Revolution EVO, and GE Healthcare Revolution Discovery CT scanners were used for conducting chest CT scans in accordance with the standard

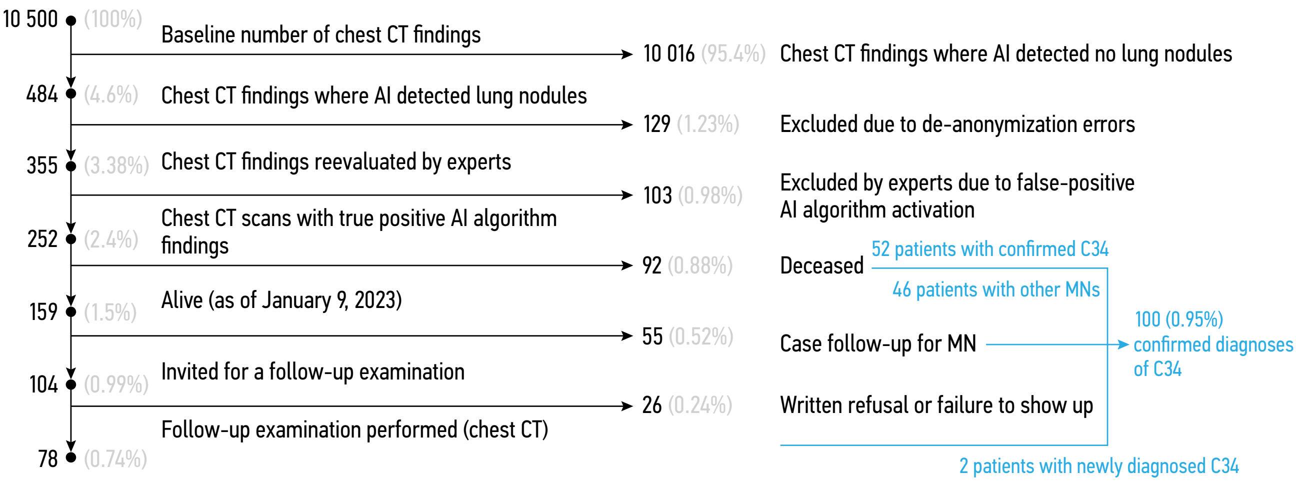

Fig. 1. Study design. CT, computed tomography; AI, artificial intelligence; MN, malignant neoplasm; C34, malignant neoplasm of the bronchus and lung according to the International Classification of Diseases, 10th revision.

protocol: X-ray tube voltage 120 kV with automated tube voltage selection; rotation time 0.50 s; pitch 0.938; slice thickness 1 mm.

All CT findings included in the study were processed using the Chest-IRA AI algorithm (LungNodules-IRA, v4.0). This algorithm was validated using a dedicated calibration dataset obtained in the Moscow Experiment [3]. The Chest-IRA algorithm was approved for use in compliance with the rules for clinical trials involving AI-based software because it exceeded the accuracy threshold of at least an ROC AUC of 0.81 [4]. The parameters of the Chest-IRA algorithm are as follows: ROC AUC 0.96; sensitivity 0.94; specificity 0.94; and accuracy 0.94 [3].

The Chest-IRA algorithm is based on two neural networks. The semantic segmentation of lung lesions and nodules is carried out by the first neural network (N1). N1 was trained using the publicly available LIDC-IDRI dataset [5], which includes chest CT findings for 1,018 patients, with lung nodule labeling using binary masks. N1 creates a binary mask for an input image. The mask is divided into connected components; some correspond to lung nodules and lesions, while others are false positives. The second neural network (N2) classifies the connected components as true positives or false positives to lower the false-positive rate. N2 was trained using a dataset of 2,351 chest CT findings. Open data were labeled based on the coordinates of various N1 findings and classification labels.

The IRA-Labs algorithm is the first differential diagnosis algorithm based on medical sorting of chest CT results. It uses the following classification: histologically confirmed lung cancer, bacterial pneumonia, COVID-19-associated pneumonia, or no abnormalities [6].

The Chest-IRA algorithm (LungNodules-IRA, v4.0) examined the obtained images; when lung nodules of >100 mm^3 were detected, the algorithm provided their location, size, and volume. Calcifications were eliminated from the algorithm's classification of nodular lesions. The algorithm had the following limitations:

- Chest CT findings had to include at least one series of lung images with axial slices;
- The spacing between slices in a series had to be consistent (for >95% of slices) and not exceed 3 mm;
- A series had to cover an area greater than 192 × 192 × 96 mm.

Main study outcome

The study's null hypothesis was that the AI algorithm does not substantially enhance early lung cancer detection when compared to the conventional interpretation of CT findings by radiologists.

The effectiveness of the AI algorithm in detecting lung cancer was the study's endpoint. The efficacy of the algorithm was determined employing the following parameters:

- Number of lung cancer cases detected using the AI algorithm;
- Proportion of early-stage (I–II) lung cancer cases detected;
- Sensitivity and specificity of the AI algorithm in identifying lung nodules;
- False-positive rate of the AI algorithm;
- Comparative analysis of the interpretation of CT findings by the AI algorithm and radiologists.

These parameters might be regarded as surrogate endpoints since they indirectly represent the potential impact of AI on the main objective: lowered lung cancer mortality. The true endpoint in this case was lung cancer mortality; however, its assessment necessitates long-term monitoring.

Additional study outcomes

To calculate the AI algorithm's economic impact, labor expenses were evaluated while accounting for the average income of radiologists in the Krasnoyarsk Krai. Moreover, the cost-effectiveness of treating patients with early-stage versus advanced lung cancer was assessed [7, 8]. The economic impact was also analyzed in terms of the life years gained and their potential contribution to the gross regional product.

Outcomes registration

Chest CT findings deemed abnormal according to the AI algorithm were reviewed once by one of the four radiologists at the Krasnoyarsk Regional Clinical Oncological Dispensary (named after A.I. Kryzhanovsky) with over ten years of experience in thoracic radiology.

Subgroup analysis

During the analysis of the CT scans, the patients were divided into three groups:

- Group 1 included patients with a high probability of lung cancer (images with signs of lung tumors);
- Group 2 included patients with no signs of lung cancer (false-positive algorithm activation);
- Group 3 included patients with inconclusive signs of lung cancer.

Patients in group 1 exhibited solid lung nodules with a diameter of ⩾6 mm and >5 nodules with benign signs [7]. Benign tumor indicators included areas of ground-glass opacity with a diameter of <6 mm, perifissural nodules, and benign calcification. Patients whose examination findings did not meet these criteria were placed in group 3.

Each patient's medical records were reviewed to determine the accuracy of the AI algorithm and the need for further examinations in patients with aberrant findings.

Ethical review

The study was approved by the local ethics committee of the Krasnoyarsk Regional Clinical Oncological Dispensary (named after A.I. Kryzhanovsky) (source: Meeting Minutes No. 48/1 of February 9, 2023). Since the study employed anonymized patient data, it was in accordance with all applicable legal standards for personal data and medical privacy. Each study group was allocated a unique encryption key, allowing for the subsequent identification of patients requiring additional examinations (patients with lung cancer signs) in a cancer center. Data were anonymized and forwarded to the IRA-Labs platform.

Statistical analysis

Sample calculation principles. A sensitivity evaluation with the lower bound of the 95% CI of at least 85% and an expected sensitivity of 95% required approximately 93 positive cases. A specificity assessment with the same accuracy and an expected sensitivity of 95% required approximately 93 negative cases. Given that the incidence of suspicious cases is 4.6%, a sample size of approximately 2,022 CT examinations was shown to be adequate for identifying 93 positive cases (93/0.046). Thus, the minimal recommended sample size in this study was determined to be 2,022 CT examinations. However, the study employed a substantially larger sample of 10,500 CT examinations, which enhances the statistical power and accuracy of the results.

Statistical analysis methods. Descriptive statistics (calculating absolute and relative frequencies for categorical variables) were used to assess the primary study data. For continuous data, ranges were computed; for time intervals, the median and ranges were ascertained. The economic analysis included the following: man-hours and labor expenses in rubles, treatment cost savings, potential contribution to the gross regional product, and a comparative analysis of early lung cancer detection rates in the Krasnoyarsk Krai and Russia. Thus, the study mostly employed descriptive statistics and economic analytical techniques.

RESULTS

Participants

The study analyzed 10,500 chest CT data from patients residing in the Krasnoyarsk Krai PACS (56% male, 44% female; ages 28–91 years) (Fig. 1).

Primary results

The AI algorithm identified lung cancer signs in 484 images (4.6% of cases). The results of 129 CT examinations (26.6%) were excluded from the study due to de-anonymization errors.

Radiologists categorized the 355 AI-selected photos into three groups (Fig. 2):

- Group 1 comprised patients with a high probability of lung cancer (192 images; 39.7% of the images selected by AI [1.83% of all examinations]);
- Group 2 consisted of patients with no signs of lung cancer (103 images; 21.3% of the images selected by AI [0.98% of all examinations]);
- Group 3 included patients with inconclusive signs of lung cancer (60 images; 12.4% of the images selected by AI [0.57% of all examinations]).

Fig. 3 and Fig. 4 illustrate the AI algorithm findings.

As of September 1, 2023, among the 252 patients in groups 1 and 3:

- 93 patients had succumbed by the time of the analysis:
  - 52 patients were being monitored for malignant neoplasms at the time of the study (lungs, bronchi, and other locations with lung metastases);
  - 11 patients with no lung metastases were being followed up for other malignant neoplasms;
  - 30 patients were not being monitored for cancer;

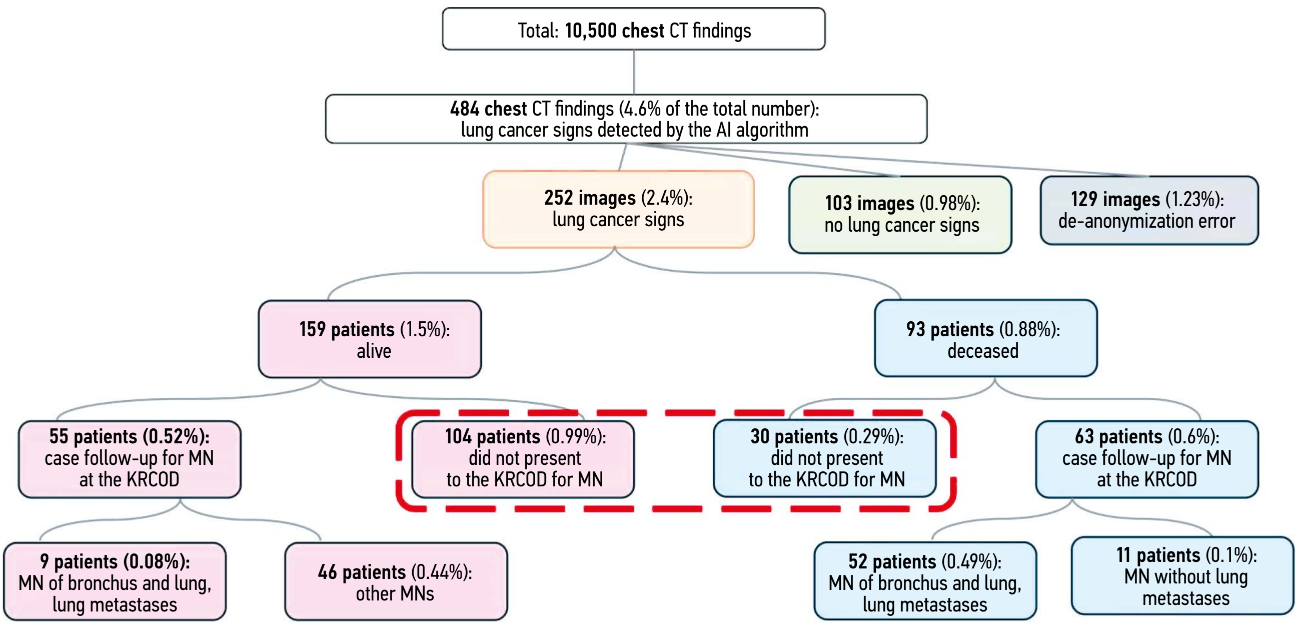

Fig. 2. Analysis of chest computed tomography findings employing artificial intelligence CT, computed tomography; AI, artificial intelligence; KRCOD, Krasnoyarsk Regional Clinical Oncological Dispensary (named after A.I. Kryzhanovsky); MN, malignant neoplasm. The red dashed line indicates that 134 people did not seek medical attention for malignant neoplasms.

- 159 patients were alive:
  – 46 patients were being followed up for malignant neoplasms at the time of the study (lungs, bronchi, and other locations with lung metastases);
  – 9 patients were being observed for other malignant neoplasms without lung metastases;
  – 10 patients experienced stage I–II lung cancer, while seven patients exhibited stage III–IV lung cancer.
- A total of 104 patients who had not sought medical care for malignant neoplasms were invited for a follow-up chest CT:
  – Nine patients submitted a formal refusal of further testing and treatment;
  – 17 patients did not show up for a follow-up examination;
  – A total of 78 patients were examined, and the diagnosis was histologically verified: two patients exhibited stage Ia and Ib lung cancer (Fig. 5), while 76 patients experienced other pulmonary diseases (Table 1).

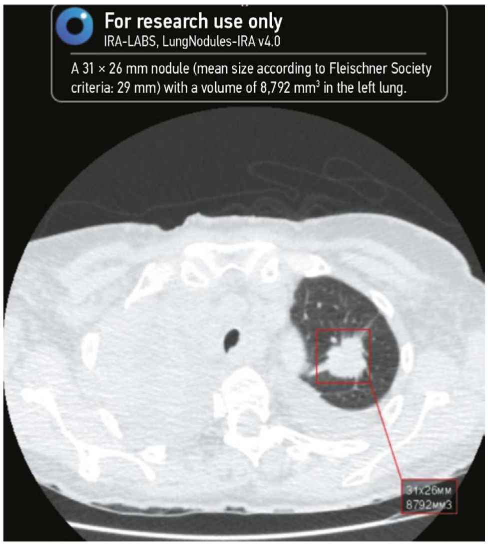

Fig. 3. Left lung nodule detected by artificial intelligence. The detected nodule is marked by the red square. Image with a high probability of lung cancer.

Thus, lung cancer was confirmed in 100 out of 355 patients (28.2%) selected using the AI algorithm.

Thirty-five percent of lung cancer cases were detected at stages I–II, while 65% were identified at stages III–IV. The lung cancer lesions in all the identified patients were histologically confirmed and analyzed based on the diagnostic date. During the seven years of follow-up prior to the use of AI, 90 lung cancer cases (90%) were identified; the remaining patients underwent a chest CT to assess treatment efficacy. In 50% of patients (n = 50), lung cancer was detected in the interval between the CT examination performed in this study and the use of AI, provided that this period was 762–881 days. Newly diagnosed lung cancer cases were identified in this study as those found following the application of AI.

The analysis of the CT findings, based on which the patients were included in group 2, revealed that the AI algorithm identified the following (Fig. 6):

- Fibrotic changes in the lung tissue in most cases (71 patients; 68.9%);
- Infiltration regions (14 patients; 13.6%);
- Hamartomas (11 patients; 10.7%);
- Lung tissue vessels (3 images).

Radiologists identified intrapulmonary lymph nodes (1.0%) and tuberculomas (1.0%) in a few isolated cases based on the results of the AI system.

The AI algorithm also detected other lung diseases.

Secondary results

Economic efficiency assessment

It is crucial to evaluate both the clinical efficacy of the experiment and the economic impact of the AI algorithm.

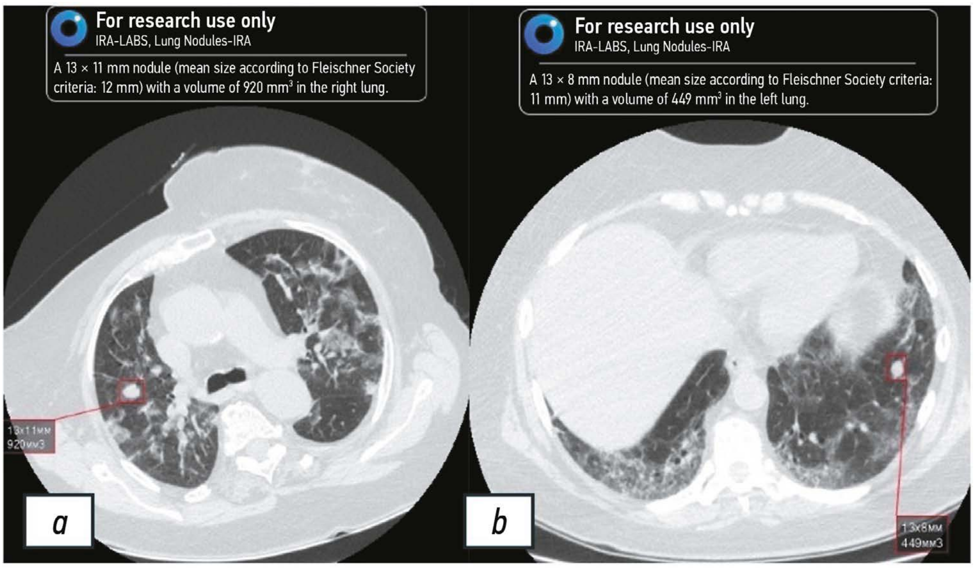

Fig. 4. Nodules in the right (*a*) and left (*b*) lungs detected by artificial intelligence. The detected nodules are marked by the red square. Images with inconclusive signs of lung cancer.

DOI: https://doi.org/10.17816/DD630885

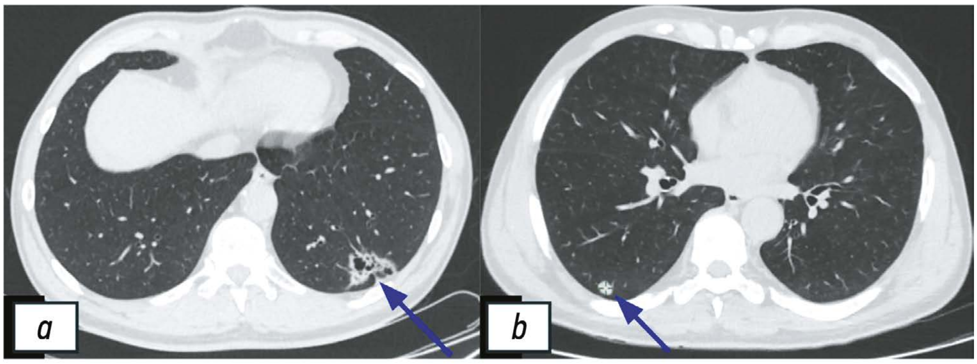

Fig. 5. Chest computed tomography findings in patients with confirmed lung cancer (blue arrows). *a*, cystic and solid mass in the left lung (stage Ia); *b*, solid mass in the right lung (stage Ib).

Table 1. Distribution of the lung lesions identified during a follow-up examination

Abnormal	Number of patients
Pulmonary hamartoma	17
Lung nodules	13
Post-inflammatory changes in the lungs	12
Tuberculoma	7
Benign neoplasm of the bronchus and lung	4
Sarcoidosis	3
Post-operative changes in the lungs	2
Pulmonary cyst	2
Fibrotic changes in the lungs	1
Chronic obstructive pulmonary disease	1
Pneumosclerosis	1
Other interstitial lung diseases with mention of fibrosis	1
Normal	12

Note. Patients diagnosed with benign neoplasm of the bronchus and lung: surgical treatment (2 patients) and consultation (2 patients) at the Krasnoyarsk Regional Clinical Oncological Dispensary named after A.I. Kryzhanovsky; a patient diagnosed with other interstitial lung disease with mention of fibrosis: surgical treatment in a cancer center (St. Petersburg).

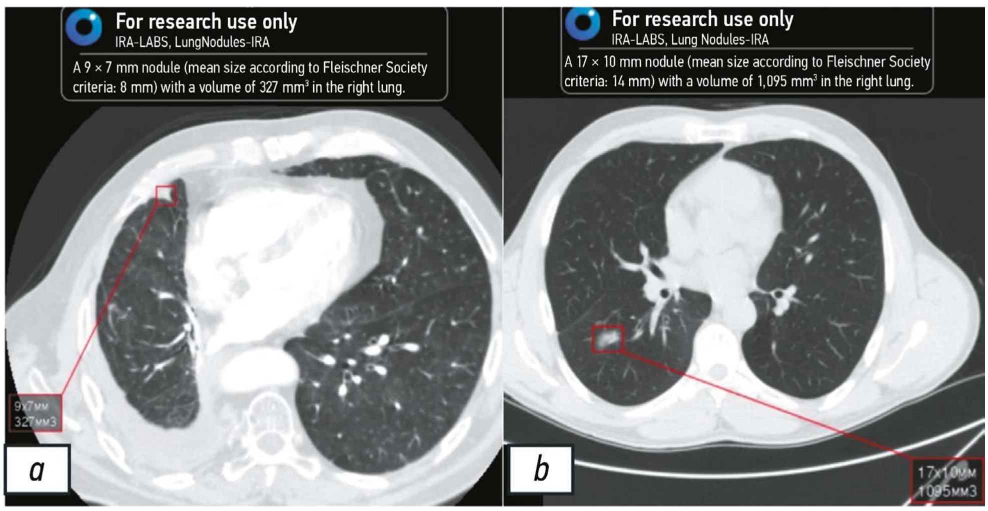

Fig. 6. Examples of the most common cases of false-positive artificial intelligence algorithm activation. *a*, fibrotic changes classified as a lung nodule; *b*, lung tissue infiltration area classified as a lung nodule.

The average pay of 96,900 rubles for radiologists in the Krasnoyarsk Krai was used to calculate potential labor costs (Table 2). A radiologist processes approximately 400 CT results per month (20 examinations per day). An initial sample of 10,500 images would therefore take a radiologist 26 months and 25 days to analyze, whereas the AI algorithm independently assessed 10,016 examinations, saving 25 months and 4 days of work. For this scope of work, a healthcare facility would need to spend 2,430 thousand rubles (which is equivalent to $27,421 or ¥196,830) on salary, excluding taxes and other payments.

Another method for assessing the effectiveness of the AI algorithms is based on the cancer treatment cost savings. Based on data from the Krasnoyarsk Regional Clinical Oncological Dispensary [named after A.I. Kryzhanovsky], at 2023 prices, the average cost of treating stage I–II lung cancer is 352 thousand rubles ($3,872 or ¥28,512) per patient. This means that the total cost of treatment for 35 patients in the early stages of the disease will be 12,350 thousand rubles ($135,811 or ¥1,066,000) (Table 3). Assuming an average treatment cost of 587 thousand rubles ($6,465 or ¥47,606), patients with advanced lung cancer will incur treatment costs of 20,570 thousand rubles ($226,278 or ¥1,666,229). Thus, the anticipated direct regional budget savings resulting from the detection of patients with early lung cancer will be 8,220,000 rubles ($90,466 or ¥666,162) per 10,500 patients undergoing a chest CT.

Another commonly used method for assessing the economic impact is based on the life years gained and their potential contribution to the gross regional product. Patients with early-stage lung cancer who receive timely detection have a 90% 5-year survival rate. Thus, 157 years and 5 days of life can be saved for 35 patients. According to data from the Federal State Statistics Service for the Krasnoyarsk Krai, the financial equivalent of the life years saved can be estimated at 173,250 thousand rubles ($1,905,750 or ¥14,033,250) if the gross regional product is calculated to be 1,100 thousand rubles (Table 4).

Furthermore, as the implications of early cancer detection with AI algorithms are noted concurrently, calculated effects can be summed together. These include healthcare professional time and salary savings, reduced treatment costs, and a potential contribution to the gross regional product owing to enhanced five-year survival rates. Thus, the overall cost can be expected to be 183,009 thousand rubles ($2,022,907 or ¥14,895,949) for 35 identified patients with early lung cancer per 10,500 chest CT examinations over 5 years.

Table 2. Comparison of the financial effects on two analysis models for chest computed tomography scan results

Parameters	Model 1	Model 2
Baseline number of chest computed tomography findings	10,500	
Number of chest computed tomography findings excluded from reassessment by a radiologist	0	10,016
Number of chest computed tomography findings reassessed by a radiologist	10,500	484
Time required to reassess chest computed tomography findings (400 computed tomography scans per month)	26 months and 25 days	1 month and 21 days
Cost of reassessment by a physician (monthly salary: 96,900 rubles)	2,543,625 rubles ($27,980 or ¥206,033)	117,249 rubles ($1,290 or ¥9,497)
Physician time savings	0 months	25 months and 4 days
Financial savings (employing artificial intelligence without payment)	0 rubles	2,426,376 rubles ($26,690 or ¥196,536)

Note. Model 1: all computed tomography findings were evaluated by a radiologist. Model 2 (two-stage analysis): all computed tomography findings were assessed by the artificial intelligence algorithm; subsequently, a radiologist reassessed images with lung cancer signs.

Table 3. Estimated financial effect of lowered treatment costs in patients with advanced lung cancer attained by implementing the artificial intelligence algorithm

Parameters	Treatment costs per patient	Treatment costs in all patients identified at early stages (*n* = 35)
Treatment costs in patients with stage III–IV lung cancer (combination therapy: surgical treatment + chemoradiotherapy, excluding immunotherapy costs)	587,735 rubles ($6,465 or ¥47,606)	20,570,725 rubles ($226,278 or ¥1,666,229)
Treatment costs in patients with stage I–II lung cancer	352,757 rubles ($3,880 or ¥28,573)	12,346,495 rubles ($135,811 or ¥908,659)
Economic efficiency of mitigated treatment costs in patients with advanced lung cancer (excluding immunotherapy costs)	234,978 rubles ($2,585 or ¥19,033)	8,224,230 rubles ($90,466 or ¥666,162)

Table 4. Cumulative financial effect of artificial intelligence in reassessing computed tomography results to detect lung cancer signs

Parameters	Project savings
Radiologist salary savings	2,426,376 rubles ($26,690 or ¥196,536)
Reduced treatment costs in patients with advanced lung cancer (35 patients with early stages)	8,224,230 rubles ($90,466 or ¥666,162)
Economic impact over five years, taking into account the estimated gross regional product per life years saved	173,250,000 rubles ($1,905,750 or ¥14,033,250)
Cumulative economic impact over one year	10,650,606 rubles ($11,157 or ¥862,699)
Cumulative economic impact over five years, considering the life years saved	183,900,606 rubles ($2,022,907 or ¥14,895,949)

DISCUSSION

Summary of the primary results

During a retrospective analysis of chest CT findings using the AI algorithm, 355 cases were selected from 10,500 processed images for reanalysis by experts of the Krasnoyarsk Regional Clinical Oncological Dispensary (named after A.I. Kryzhanovsky). Based on the chest CT changes, 252 patients (2.4%) were included in groups 1 and 3. There were 35 patients with stage I–II lung cancer and 65 patients with stage III–IV lung cancer. The expected direct regional budget savings resulting from the detection of patients with early lung cancer was estimated to be 8,220,000 rubles ($90,466 or ¥666,162) per 10,500 patients undergoing a CT scan.

Discussion of the primary results

In most patients, the Chest-IRA AI algorithm reliably diagnosed lung nodules with a high or moderate probability of lung cancer secondary to COVID-19-associated inflammatory alterations. These data support the efficacy of the hybrid retrospective assessment of chest CT findings. Notably, the average proportion of detected early lung cancer cases (stages I–II) in Russia does not exceed 30% [9]. This is partly due to the inadequate efficacy of photofluorography conducted during medical check-ups in adults in terms of early lung cancer diagnosis. Detecting neoplasms larger than 1 cm, even with modern X-ray technologies, demands skilled radiologists and patient-specific examination of risk factors, such as family history, occupational factors, and infectious or chronic diseases. Thus, X-ray tests typically detect advanced lung cancer, where curative therapy is not feasible, and the prognosis is generally unfavorable [10].

High-quality, timely screening for lung cancer is a potential solution to this issue. Low-dose computed tomography (LDCT) is the most effective technique; it detects twice as many small foci and three to four times as many focal lesions as X-ray imaging. The National Lung Screening Trial, the most extensive study on the subject conducted in the USA, demonstrated that LDCT as a screening tool lowered lung cancer mortality by 16% compared to chest X-ray [10]. In selected adult populations, LDCT has been recommended as a lung cancer screening method during physical examinations since 2015 as part of a pilot project in Krasnoyarsk[1]. *n*LDCT was performed in high-risk patients who met all the following criteria: males aged 50–64 years residing in Krasnoyarsk with a smoking index ⩾30. Between 2015 and 2017, when LDCT was incorporated into the lung cancer screening protocols, the lung cancer detection rate was 17.1 per 1,000 examined high-risk patients, which was 30 times higher than that of photofluorography or X-ray imaging (0.57 per 1,000 examined patients) [11]. This strategy has been used across Krasnoyarsk Krai since 2018. It was included in the medical check-up standards for selected adult populations in 2019, along with an expansion of the high-risk criteria (Fig. 7).

The use of LDCT as a lung cancer screening tool between 2015 and 2021 improved the early lung cancer detection rate; in the Krasnoyarsk Krai, the detection rates became higher than the Russian average. In the Krasnoyarsk Krai, the early lung cancer detection rate improved from 22.1 per 100,000 population in 2015–34.2 per 100,000 population in 2021 (a 54.8% increase). From 27.3 per 100,000 people in 2015 to 29.6 per 100,000 population in 2021 (an 8.4% rise), the average early lung cancer detection rate in Russia improved. Moreover, between 2015 and 2021, the Krasnoyarsk Krai experienced a decline in lung cancer mortality by 7.0% (from 48.7 to 45.3 per 100,000 population), in contrast to the Russian average, which increased by 13.2% (from 34.1 to 38.6 per 100,000 population) during the same period [2].

Recent research indicates that AI is as accurate as radiologists in predicting the risk of lung cancer. Complex lung cancer screening using AI algorithms demonstrates high efficacy (ROC AUC 94.4%) and improves the accuracy of radiologist conclusions, with an absolute reduction in the false-positive and false-negative rates by 11% and 5%, respectively [11]. A recent systematic review that evaluated the effectiveness of AI in diagnosing and predicting lung cancer

[1] Letter of the Ministry of Health of the Krasnoyarsk Krai No. 71/08-26/9923 of May 15, 2015. On Lung Cancer Screening in Medical Check-up Programs for Selected Adult Populations

Fig. 7. Evolution of lung cancer screening in the Krasnoyarsk Krai.

found that radiologists utilizing AI algorithms were more accurate in their examination of CT scan results. AI algorithms predict tumor grade reliably and accurately, as indicated by the method's high sensitivity and specificity [12].

Goncalves et al. [13] employed SWOT analysis to ascertain the advantages, disadvantages, opportunities, and risks of using AI algorithms to detect lung cancer. The advantages included the high accuracy of modern algorithms, reduced workload, and a lowered risk of errors in lung cancer diagnosis. The main disadvantage, as per the authors, is the need for real-world validation studies before implementation in clinical practice. The risks included confidentiality and data security concerns, as well as the use of biased samples for algorithm training. In 21.3% of all CT scans in which the AI system identified lung nodules (103 images), experts observed false-positive AI algorithm activation. In most cases (71 images; 68.9%), the AI algorithm incorrectly classified areas of lung tissue scarring as signs of lung cancer. The absolute number was within the permissible range for review, even though the false-positive AI algorithm activation rate was comparatively high. Moreover, the project primarily aimed to detect the maximum number of patients with suspected lung cancer based on chest CT findings obtained during the COVID-19 pandemic. For this purpose, a low AI algorithm activation threshold was employed. However, a reduction in the target parameters may occur when specificity is prioritized over sensitivity when establishing the AI activation threshold. As specificity increases, the rate of false-positive AI findings (and workload) and the number of findings also increase, contributing to the risk of undetected lung cancer.

Ziegelmayer et al. [14] used the Markov model to determine the economic efficiency of an AI algorithm during the first stage of lung cancer screening. The authors concluded that utilizing AI during primary screening saves $1,240 per patient, with a willingness to pay $100,000 for quality-adjusted life years, confirming the economic efficiency of this approach. Both during the study and five years later, our method of reanalysis of chest CT findings using AI for the detection of lung cancer signs can also be considered economically feasible. Life years gained, lower treatment costs for patients with advanced disease, and a notable reduction in the need for doctors to reevaluate chest CT results—all of which take into account the patients' potential future economic contribution to the area—are indicators of cost savings. The cumulative effect (salary savings, reduced treatment costs, and potential contribution to the gross regional product) over five years is estimated at 183,900 thousand rubles ($2,022,907 or ¥14,895,949). However, since the following two patient groups were left out of our estimates, the overall economic benefits might be greater:

- Patients with de-anonymization errors;
- Patients who received a postmortem cancer diagnosis between the time of the chest CT scan and the commencement of the retrospective study.

If the data of all 484 patients were analyzed, with no de-anonymization errors and an early-stage distribution comparable to that of the 355 patients included in the analysis, the number of patients with early lung cancer identified using AI would be 43. Thus, the cumulative economic impact (2,430 thousand rubles + 10,105 thousand rubles + 236,005 thousand rubles from reassessment, lowered treatment costs, and life years saved, respectively) was 249,080 thousand rubles ($2,739,880 or ¥20,175,480) over five years.

Study limitations

This study has several limitations. First, there is its retrospective design; nevertheless, the design aligned with the study aim. Second, only the results where the AI algorithm identified lung nodules greater than 100 mm^3 were reevaluated by a radiologist. This was done to preserve resources and time when reevaluating large datasets. The economic efficiency assessment did not consider lowered immunotherapy costs in patients with advanced disease, as well as indirect costs. Another limitation is that the AI algorithm was developed to detect lung nodules rather than lung cancer. Thus, the AI algorithm findings encompassed diverse conditions, which necessitated additional studies to confirm lung cancer.

CONCLUSION

The use of AI technology to analyze large sets of chest CT scans conducted for various indications may contribute to ancillary lung nodule detection. This includes CT findings from screening programs or examinations for lung diseases other than lung cancer, such as COVID-19. The Chest-IRA AI algorithm has demonstrated encouraging results. However, additional research is required to determine the efficacy and safety of this algorithm in real-world practice. Further information is needed on how AI technology affects lung cancer detection rates and the feasibility of incorporating it into current diagnostic processes. It is crucial to continue research and clinical trials in this promising but inadequately studied area.

ADDITIONAL INFORMATION

Funding source. This study was not supported by any external sources of funding.

Competing interests. The authors declare that they have no competing interests.

Authors' contributions. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work. R.A. Zukov — conceptualization of the study, expert evaluation of information, and approval of the final manuscript version; I.P. Safontsev — conceptualization of the study, literature search on the article's topic, expert evaluation of information, and manuscript text editing; M.P. Klimenok — expert evaluation of information and manuscript text editing; T.E. Zabrodskaya — literature search on the article's topic, data set formation, analysis of study results, and manuscript writing; N.A. Merkulova — data set formation, analysis of study results, expert evaluation of information, and manuscript writing; V.Yu. Chernina — literature search on the article's topic and manuscript writing; M.G. Belyaev — expert evaluation of information and manuscript text editing; M.Yu. Goncharov — data analysis; N.A. Omelyanovsky — expert evaluation of information and manuscript text editing; K.A. Ulyanova — expert evaluation of information; E.A. Soboleva, M.E. Blokhina, E.A. Nalivkina — literature review and manuscript text editing; V.A. Gombolevsky — developed the study concept, conducted expert information evaluation, authored the manuscript, and approved its final version.

Acknowledgements. The team of authors would like to thank AstraZeneca for providing their expertise and scientific support.

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DOI: https://doi.org/10.17816/DD630885

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