DOI: 10.14739/mmt.2024.3.310341 Оригінальні дослідження / Original research
UDC 616-006.6-02:665.16:613.67.02

The use of a trench candle as an alternative heating and light source in wartime and possible negative consequences

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A – research concept and design; B – collection and/or assembly of data; C – data analysis and interpretation; D – writing the article; E – critical revision of the article; F – final approval of the article

Keywords: trench candle, ultrafine aerosol, carcinogenic risk, military personnel.

Aim. To examine the composition of ultrafine aerosol in the air generated by the trench candle burning and compare combustion products with proven carcinogens according to the International Agency for Research on Cancer (IARC) classification.

Materials and methods. The content of ultrafine aerosol emitted from trench candle burning was studied using a NanoScan 3910 portable scanning spectrometer. The number, area, surface volume and mass concentration of particles were measured at 0.5 and 1.5 meters above the floor level before and after the trench candle burning for 10 minutes. The chemical composition was assessed by inductively coupled plasma optical emission spectrometry (ICP-OES, PerkinElmer Optima 2100 DV, USA). The morphological characteristics of suspended particles were studied by scanning electron microscopy (TESCAN VEGA3, Czech Republic).

Results. High concentrations of suspended particulates in the ultrafine particle size range outnumbering the background content by almost 985 times ($p \leq 0.001$) have been found to be emitted from the trench candle burning into the indoor air at the breathing level. The ultrafine aerosol contained carcinogenic heavy metals according to the IARC classification (chromium, cadmium, and cobalt).

Conclusions. The use of trench candles during the Russian–Ukrainian war relates military and civilian populations to a risk group, that requires wartime carcinogenic effects on the Ukrainian population to be studied and demands the development of a National Program for primary and secondary prevention of cancer as soon as today.

Modern medical technology. 2024;16(3):165-174

Ключові слова: окопна свічка, ультрадисперсний аерозоль, ризик, військовослужбовці.

Надійшла до редакції / Received: 19.07.2024

Після доопрацювання / Revised: 22.08.2024

Схвалено до друку / Accepted: 27.08.2024

Конфлікт інтересів: відсутній.

Conflicts of interest: authors have no conflict of interest to declare.

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Використання окопної свічки як альтернативного джерела опалення й світла у військовий час і можливі негативні наслідки

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Мета роботи – вивчити склад ультрадисперсного аерозолю в повітрі під час горіння окопної свічки та порівняти продукти згоряння з доведеними канцерогенами за класифікацією Міжнародної агенції з дослідження раку (IARC).

Матеріали і методи. Вміст ультрадисперсного аерозолю в повітрі під час горіння окопної свічки вивчили за допомогою портативного сканувального спектрометра NanoScan 3910. Визначили кількість, площу, об'єм поверхні та масову концентрацію частинок до та після горіння окопної свічки протягом 10 хв на висоті 0,5 м та 1,5 м від підлоги. Хімічний склад визначили методом оптично-емісійної спектрометрії з індуктивно зв'язаною плазмою (ICP-OES), використавши прилад Optima 2100 DV (PerkinElmer, США). Морфологічні особливості зважених частинок вивчили методом сканувальної електронної мікроскопії TESCAN VEGA3 (Чехія).

Результати. У результаті досліджень встановлено, що під час горіння окопної свічки у повітрі приміщення на висоті рівня дихання людини утворилася велика концентрація зважених частинок ультрадисперсного діапазону, кількість яких перевищувала фоновий вміст майже в 985 разів ($p \leq 0{,}001$). До складу ультрадисперсного аерозолю входили канцерогенні важкі метали за класифікацією IARC (хром, кадмій і кобальт).

Висновки. Під час російсько-української війни військовослужбовці та цивільне населення є групою ризику внаслідок застосування окопних свічок. Тому доцільно вивчати вплив канцерогенів, що актуалізовані воєнним часом, на населення України. Необхідно якнайшвидше розробити державну програму первинної та вторинної профілактики онкологічних захворювань.

Сучасні медичні технології. 2024. Т. 16, № 3(62). С. 165-174

High-intensity wars seriously damage health of military and civilian populations. At the moment of explosions and building collapses, humans are exposed to hazardous substances, the concentration of which increases dramatically in the environment [1]. Such substances include smoke, sand, dust, asbestos, crushed stone, demolition waste, which are a source of carcinogenic solid particles in ambient air [2].

Military industry workers and military personnel are at a higher risk for postwar respiratory cancer development as compared to the general population [3,4,5]. The problem can be caused not only by weapons containing toxic components, but also by household products daily used at the front line. These include the so-called trench candle, which has been known since World War I, also named after Paul von Hindenburg, a German Field Marshal General and statesman [6]. This device has gained popularity in Ukraine since the beginning of the Russian–Ukrainian war. It is used as a can filled with porous material of cardboard boxes and melted wax or paraffin poured over. Tens of thousands of such candles find applications in the front-line trenches and among the civilian population in the regions adjoining the conflict zone for lighting, heating, cooking, and clothes drying.

Composition of smoke from the trench candle burning and its effects on the military personnel health have not yet been examined.

Aim

To examine the composition of ultrafine aerosol generated by the trench candle burning and compare combustion products with proven carcinogens according to the International Agency for Research on Cancer classification.

Materials and methods

The composition and physical properties of the ultrafine aerosol produced by the trench candle burning were studied in a closed room of 30 m^3 (4.0 × 3.0 × 2.5 meters) for 10 minutes. The obtained parameters were compared with the background concentration of suspended particles in the air before the trench candle use.

The ultrafine aerosol composition was examined using a portable scanning spectrometer NanoScan 3910 (USA), which measures the content of suspended particles in the range from 10 nm to 400 nm with the maximum measurement capability of detecting the total concentration of up to 1,000,000 particles per 1 cm^3 *(Fig. 1)*. Particles with an aerodynamic diameter ≤100 nm were referred to as ultrafine. For each size range of suspended particles, the number (number/cm^3), area (nm^2/cm^3), surface volume (nm^3/cm^3) and mass concentration (μg/m^3) were determined. A total of 195 measurements were made, including 65 before the trench candle burning (background concentrations of suspended particles) and 65 measurements each at 0.5 and 1.5 meters above the floor level after the trench candle burning for 10 minutes.

The chemical composition of suspended particles was assessed by inductively coupled plasma optical emission spectrometry (ICP-OES, PerkinElmer Optima 2100 DV, USA) [NIOSH, 2001, National State Standard ISO 15202-2008]. Air sampling was conducted at the breathing zone level with a 0.50 L/min volumetric flowrate in a total volume of 5 liters using a TYPHOON P-20-2 sampler through a Zaitsev absorber containing deionized water for 10 minutes. The resulting solution was transferred from absorbers into test tubes for the subsequent determination of the elemental composition by the ICP-OES method. ICP multielement standard solution containing 23 chemical elements No. 111355.0100 (Merck, Germany) was used to calibrate the device.

The most sensitive wavelength was selected for each element from the WinLab32 library of the ICP-OES device. A total of 20 toxic metals and essential trace elements (Al, Cr, Si, Fe, Mn, Mo, Ni, Ca, Mg, P, W, Ti, Pb, Sn, Cd, Zn, Co, Cu, As, V) were quantified in accordance with the metrological requirements for the device, which are listed in *Table 1*.

For ensuring quantification accuracy, all the measurements were performed twice. Therefore, the experimental value was considered accurate if the relative standard deviation did not exceed 2 %. External quality assurance of laboratory analyses in determining the content of toxic metals and essential trace elements was carried out following the program of interlaboratory comparisons of chemical elements in the air jointly with E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine (Kyiv) in 2024.

Mathematical processing of the obtained results was carried out using the WinLab32 software for device ICP-OES and the Windows XP Professional operating system, and statistical analysis was done using the Microsoft Excel program package according to [7].

The data on the morphological characteristics of suspended ultrafine particles were obtained by the method of scanning electron microscopy (TESCAN VEGA3, Czech Republic) at 20 kV accelerating voltage. Images were taken in secondary electron (SE) and backscattered electron (BSE) detection modes. The local chemical composition of the captured particles was assessed by energy-dispersive X-ray spectroscopy (EDX) using an XFlash Detector 610M spectrometer (Bruker, Germany).

The obtained results were calculated mathematically on a PC using the licensed software "Statistica version 13" (Copyright 1984–2018 TIBCO Software, license No. JPZ804I382130ARCN10-J). Descriptive statistics were presented as median with interquartile range – Me (Q25; Q75) since the obtained variables were non-normally distributed. Significant differences between the compared values were analyzed by the Mann–Whitney test. Differences were considered to be statistically significant at a p-value <0.05.

Results

The studies provided data on the suspended particle number at different indoor levels (background concentration) and after 10 minutes of the trench candle burning.

In the background mode, the highest concentration of suspended particles was observed in the range of 27.4 nm – 747.29/cm^3 (747.14; 747.98) and 36.5 nm – 696.74/cm^3 (675.77; 697.04), the lowest – particles ranging 365.2 nm – 25.58/cm^3 (24.01; 44.63) in sizes *(Fig. 2a)*. The suspended particle number

Fig. 1. Examination of ultrafine aerosol after the 10-minute trench candle burning using the portable scanning spectrometer NanoScan 3910 (USA).

of different aerodynamic diameters was considerably increased in all parameters being statistically significantly higher ($p \leq 0.001$) 10 minutes after the trench candle burning at 0.5 m *(Fig. 2b)* and 1.5 m *(Fig. 2c)* above the floor level as compared to the background concentrations.

In addition to the suspended particle number, other parameters of the ultrafine aerosol increased rapidly: the surface area, volume, and total mass concentration of solid particles in all sizes with significant differences ($p \leq 0.05$) compared to those before the trench candle burning.

The total particle surface volume increased from 5.93×10^{11} to 1.43×10^{12} nm^3/cm^3 at 1.5 meters above the floor level after the trench candle burning.

The mass concentration indicators of differently sized suspended particles during the trench candle burning at various levels were statistically significantly different in almost all dimensions. The obtained results are presented in *Fig. 3* and *Table 2*.

The findings on a significant increase in the surface area of suspended particles after the trench candle burning are indicative of their high biological activity allowing them to additionally adsorb numerous pollutants and easily transport them from the environment into the human respiratory tract.

Measuring the physical parameters of the ultrafine aerosol composition during the trench candle burning in the indoor environment for more than 10 minutes was impossible, since the device parameters were not designed for studying such values.

Ultrafine aerosol chemical composition during the trench candle burning was analyzed by the method of optical emission spectrometry; these data are shown in *Table 3.* The presence of chromium (Cr), silicon (Si), calcium (Ca), wolfram (W), cadmium (Cd), zinc (Zn) and cobalt (Co) was detected in the air at concentrations which did not exceed permissible exposure limits (PELs) in the workplace air [8].

Using the method of scanning electron microscopy, the morphological features of individual suspended particles emit-

Table 1. Metrological parameters for determining the content of toxic metals and essential trace elements in the air by the ICP-OES method (axially viewed plasma – XL)

Chemical element	Wavelength, nm	Limit of quantitation by the method (LOQ, µg/l)	Similarity of two tested parallel samples, %
Al (Aluminium)	396.153	0.0003	0.88
As (Arsenic)	193.696	0.003	2.25
Ca (Calcium)	422.673	0.003	0.45
Cd (Cadmium)	228.802	0.00016	0.56
Cu (Cuprum)	324.752	0.00020	1.50
Co (Cobalt)	230.786	0.0002	2.13
Cr (Chromium)	283.563	0.0002	2.28
Fe (Ferrum)	259.939	0.0003	0.35
Mn (Manganese)	257.610	0.00010	2.21
Mg (Magnesium)	279.077	0.003	0.57
Mo (Molybdenum)	203.485	0.0005	1.98
Ni (Nickel)	231.604	0.002	2.23
S (Sulfur)	189.965	0.004	2.62
Si (Silicon)	283.998	0.006	2.69
Sn (Stanum)	235.485	0.004	1.24
Ti (Titanium)	334.940	0.0002	2.08
P (Phosphorus)	213.617	0.01	1.66
Pb (Plumbum)	220.353	0.002	2.10
Zn (Zinc)	206.200	0.002	1.99
V (Vanadium)	270.093	0.001	1.89
W (Wolfram)	239.708	0.0002	1.09

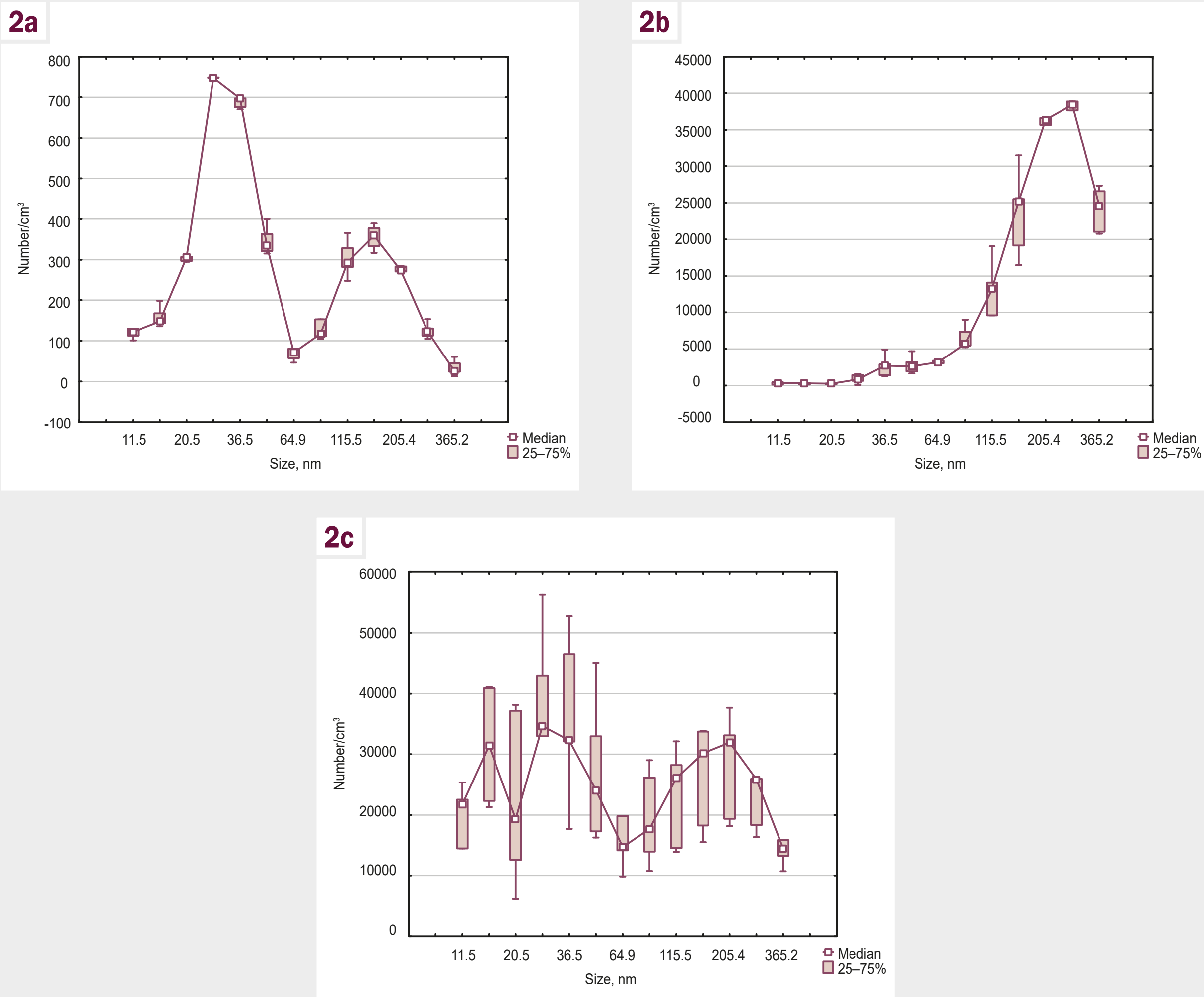

Fig. 2. The number of suspended particles before using the trench candle (**a**) and after the trench candle burning (**b, c**) for 10 minutes (number/cm^3).

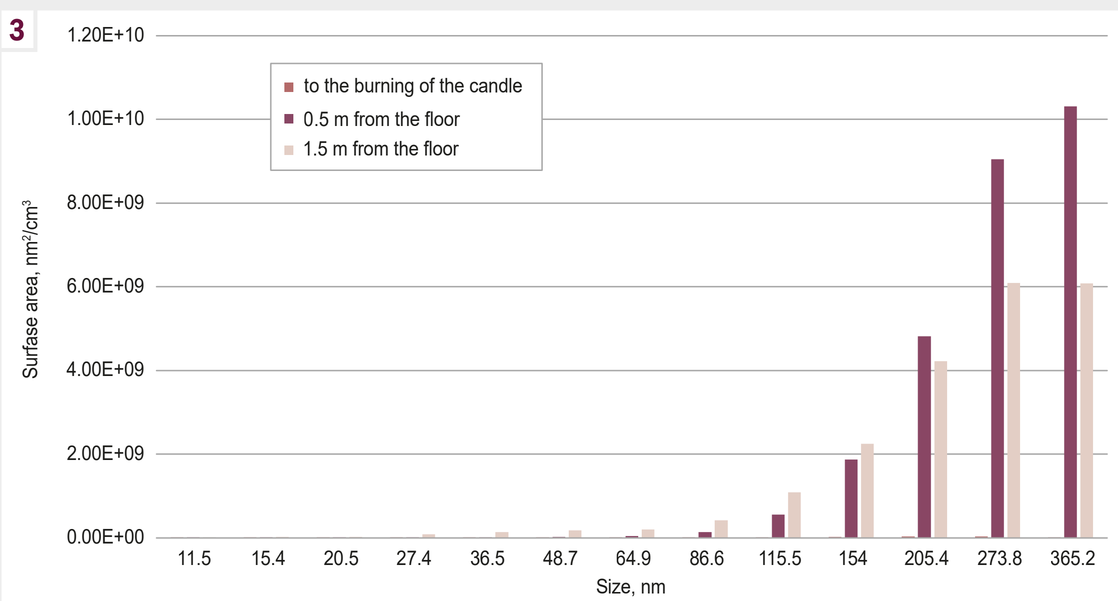

Fig. 3. Surface area of differently sized suspended particles in the air before and after the trench candle burning, nm^2/cm^3.

Table 2. Mass concentration of suspended ultrafine aerosol particles in the air before and after the 10-minute trench candle burning at different levels, μg/m^3, Me (Q25; Q75)

Particle size, nm	Before the trench candle burning, n = 65	After the 10-minute trench candle burning at 0.5 m above the floor level, n = 65	After the 10-minute trench candle burning at 1.5 m above the floor level, n = 65
11.5	0.0001 (0.0001; 0.0001)	0.0003 (0.0001; 0.0004)	0.021 (0.014; 0.022)*
15.4	0.0003 (0.0003; 0.0004)	0.0007 (0.0003; 0.0008)	0.058 (0.051; 0.093)*
20.5	0.0017 (0.0016; 0.0017)	0.0014 (0.0011; 0.0016)	0.105 (0.068; 0.202)*
27.4	0.0096 (0.0096; 0.0097)	0.0108 (0.0084; 0.0188)	0.447 (0.425; 0.554)*
36.5	0.0213 (0.0207; 0.0213)	0.0830 (0.0439; 0.0889)*	0.987 (0.982; 1.421)*
48.7	0.0243 (0.0233; 0.0264)	0.1904 (0.1399; 0.2343)*	1.749 (1.257; 2.390)*
64.9	0.0122 (0.0099; 0.0139)	0.5206 (0.4381; 0.5843)*	2.539 (2.446; 3.416)*
86.6	0.0478 (0.0454; 0.0623)	2.3253 (2.2253; 2.9992)*	7.230 (5.713; 10.668)*
115.5	0.2837 (0.2732; 0.3180)	12.7760 (9.2664; 13.6509)*	25.192 (14.102; 27.292)*
154	0.8241 (0.7643; 0.8669)	57.7962 (43.9879; 58.5199)*	69.149 (41.964; 77.340)*
205.4	1.4873 (1.4758; 1.5417)	197.8996 (194.0988; 199.3340)*	172.607 (105.513; 180.048)*
273.8	1.5877 (1.4527; 1.6810)	495,8106 (485.7798; 501.5460)*	333.693 (237.116; 334.745)*
365.2	0.7828 (0.7346; 1.3654)	753.1634 (643.7714; 813.1595)*	444.137 (405.180; 486.213)*

*: statistically significant differences with the indicators in the air before the trench candle burning (≤ 0.001)

Table 3. The content of chemical elements in the air after the 10-minute trench candle burning, mg/m^3

Chemical element	Concentration in air after the 10-minute trench candle burning	PEL* of chemicals in the workplace air
Chromium (Cr)	0.016–0.020	1.0
Silicon (Si)	0.50–0.60	1.0
Calcium (Ca)	0.60–0.78	1.0
Wolfram (W)	0.60–0.82	6.0
Cadmium (Cd)	0.0001–0.001	0.05
Zinc (Zn)	0.123	0.5
Cobalt (Co)	0.0003	0.05

*: according to the Order of the Ministry of Health of Ukraine No. 1596 dated 14.07.2020 "On the approval of hygienic regulations for the permissible content of chemical and biological substances in the air of the working area" [8].

ted during the trench candle burning were determined and their elemental composition was assessed *(Fig. 4,5).*

High percentage of copper (Cu) and aluminum (Al) in the chemical composition was detected due to the use of copper grids to fix the suspended particles on an aluminum table and was ignored.

In the samples *(Fig. 4 a–c),* suspended particles were detected containing calcium (0.34 %), potassium (0.12 %), silicon (0.5 %), magnesium (1.28 %), sulfur (0.14 %) and the largest amount of carbon (65.60 %), which is a product of incomplete combustion (soot formation) during the trench candle burning.

Some of the particles (*Fig. 5 a–c)* were found with a high content of chromium (64.7 %), that according to the International Agency for Research on Cancer (IARC) classification is a proven Group 1 human carcinogen, and some even contained the chemical element bismuth.

Discussion

Observations have shown that wars dramatically increase the incidence of lung cancer in civilian and military populations. As a matter of fact, by 1898, only 140 cases of this tumor had been described in the medical literature. In the book dated 1912 "Primary Malignant Growths of the Lungs and Bronchi", Isaac Adler claimed that "lung tumors are one of the rarest forms of cancer" [9]. 15 years after the end of World War I, lung cancer mortality was already 4.9 per 100,000 male population and continued to

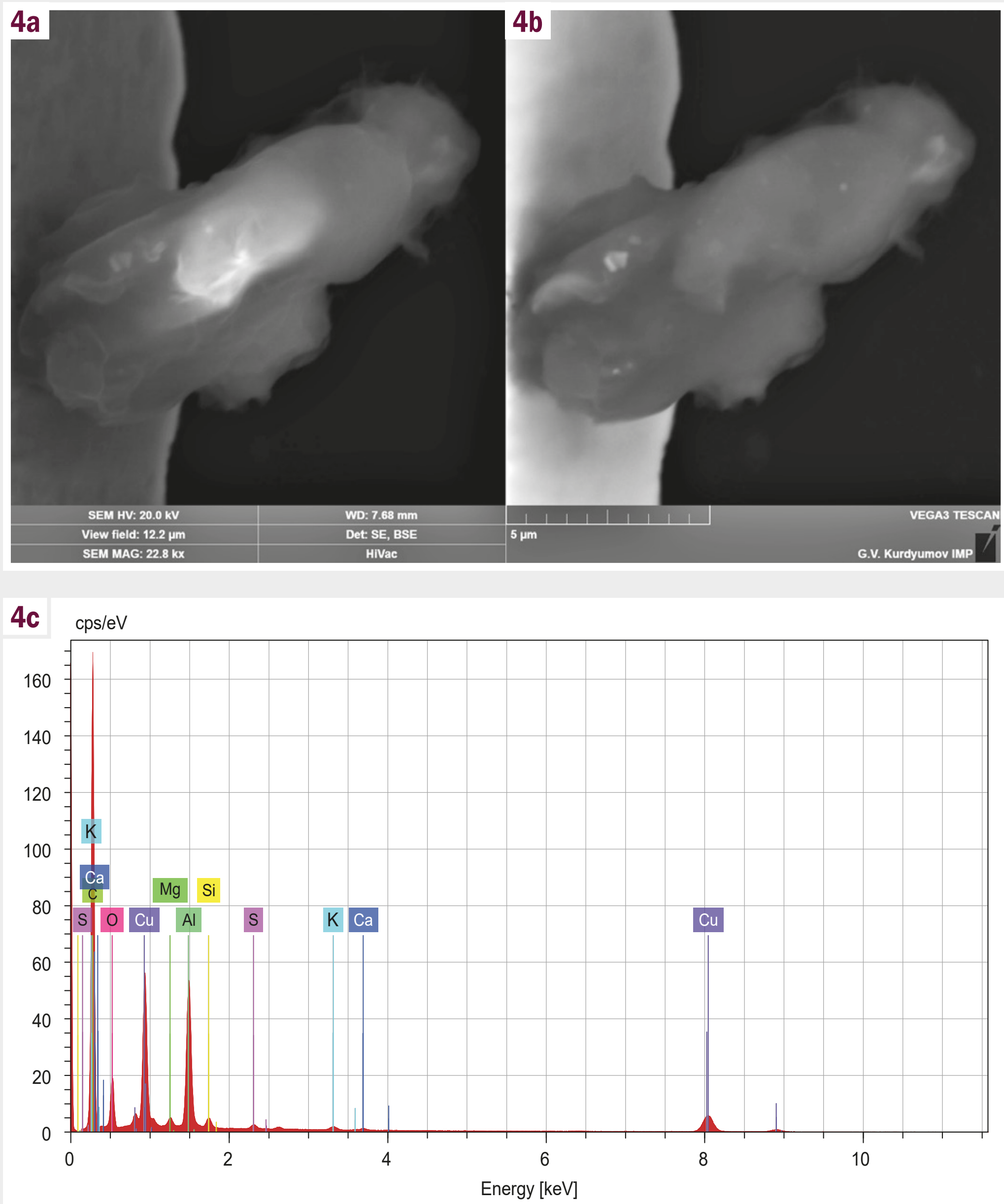

Fig. 4. Findings obtained via scanning electron microscopy on morphological features **(a,b)** and chemical composition **(c)** of suspended ultrafine particles in the air after the 10-minute trench candle burning.

increase throughout the XX century. It was initially related to latent effects of toxic gases, long-term outcomes of pandemic influenza, fogs, lack of sunlight exposure, common cold, and X-rays.

In 1950, the Britons Richard Doll and Austin Hill outlined two potential reasons for a sharp rise in lung cancer cases. They considered mass tobacco smoking and global environmental pollution by motor vehicle emission, dust from asphalt roads, smoke emitting from factories and industries, coal fires [10].

The World Health Organization estimates that air pollution is responsible for about 7 million deaths each year worldwide, which is comparable to the death rate from tobacco smoking [11]. 80 % of these deaths are due to non-communicable diseases. Long-term air pollution exposure is closely related to the increased risk of death from coronary heart disease, chronic obstructive pulmonary disease, stroke as well as developing type II diabetes mellitus, obesity, Alzheimer's disease, and dementia [12,13,14].

Atmospheric carcinogens are involved in the pathogenesis of lung, breast, prostate, colon, stomach, liver, nasopharynx, larynx, esophagus, pancreas, kidney, bladder, ovary, cervix, and myeloid leukemia cancers [15].

In ambient air, toxic and carcinogenic substances are strongly adsorbed on solid particles. This is a large class of chemically and physically diverse aerosols suspended in the air. They differ in size, origin, chemical composition, and behavior in the atmosphere [16,17,18].

Coarse particulate matter (PM) with aerodynamic diameter of more than 10 μm is usually trapped in the upper respiratory

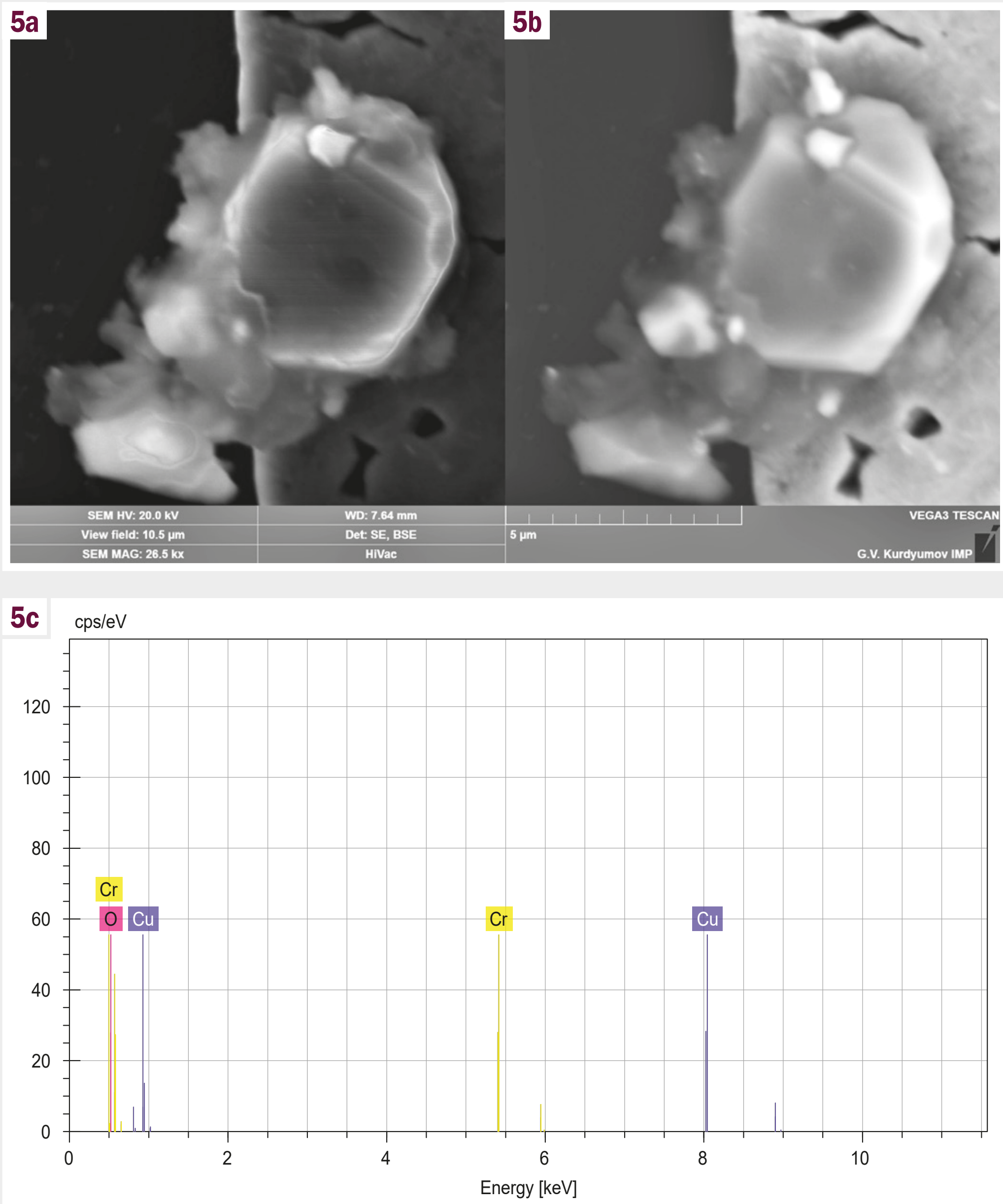

Fig. 5. Findings obtained via scanning electron microscopy on morphological features **(a,b)** and chemical composition **(c)** of suspended ultrafine particles in the air after the 10-minute trench candle burning.

tract and does not deposit in the lungs. These particles can move up to tens of kilometers from emission sources. PM with a smaller diameter can float in the atmosphere for up to several weeks and travel hundreds or thousands of kilometers. Fine and ultrafine PM of combustion products with a diameter of ≤2.5 µm and ≤0.1 µm, respectively, cannot be filtered by the respiratory system and penetrate deep into the lungs, remaining active in the human body 40 times longer than the ingredients of cigarette smoke.

These toxic pollutants pose a risk for lung cancer that is 12 times higher than that in passive smokers. Coarse PM and gases cause chronic low-grade inflammation and oxidative stress in human tissues. In bronchial epithelial cells exposed to different concentrations of $PM_{2.5}$, DNA damage and transcriptional changes occur in hundreds of genes involved in the inflammatory and immune response [19].

Along with liquid- and solid-phase water- and fat-soluble compounds, solid graphite carbon, metals and viscous organic liquids also penetrate into the lung alveoli. They bind at least 500 different chemical classes of organic and inorganic substances that can cause DNA mutations.

Although exposure to both coarse (PM_{10}) and ultrafine ($PM_{0.1}$) airborne particles can cause detrimental effects on health, long-term exposure to $PM_{2.5}$ is the main cause of mortality from cardiovascular, respiratory diseases and cancer [20,21,22].

In 2019, 307,000 premature deaths were estimated to be attributable to $PM_{2.5}$ in the 27 European Union Member States. In addition to cancer, combustion products can cause coronary thrombosis, stroke, pulmonary emphysema, asthma, and pneumonia [23,24].

Our studies have suggested that the smoke from the trench candle burning is a typical ultrafine aerosol containing heavy metals and consisting of a complex mixture of gases, soot, ash, and resinous substances. There are reasons to believe that the presence of chromium, cadmium, and cobalt in solid nanoparticles could have negative consequences on the human body due to their ability to easily cross the air-blood barrier, gain access to the systemic circulation and reach various organs and body systems via the blood flow.

According to the IARC classification, hexavalent chromium (Cr) and cadmium (Cd) are Group 1 (proven) human carcinogens, and cobalt compounds are classified as possibly carcinogenic to humans (Group 2B) [25]. Hexavalent chromium is particularly carcinogenic. Its effects are associated with the development of lung cancer, cancer of the nasal cavity and paranasal sinuses [26,27,28]. Cadmium and its compound exposures cause lung, kidney and prostate cancer [29,30,31]. Although data on the carcinogenic properties of cobalt are less conclusive, an increased risk for lung cancer has been proven to be cobalt-induced. Like chromium, cobalt can cause cancer of the nasal cavity and paranasal sinuses [32,33,34].

Other elements that were detected after the trench candle burning, such as silicon (Si), calcium (Ca), tungsten (W), zinc (Zn) in their usual forms and compounds do not have oncogenic effects, but human inhalation exposure to some of their forms (for example, silicon dioxide, crystalline silica) may also be associated with an increased risk for cancer [35].

To minimize adverse health impacts when using trench candles and other similar sources of smoke containing toxic and carcinogenic metals, precautions with a high level of personal protection should be recommended, including P100 respirator filters enable capturing fine particles and metal aerosols.

Epidemiological cohort studies among military personnel and civilians, who were regularly exposed to the trench candle smoke and other toxic substances, to assess the frequency and types of cancer in these risk groups will be relevant in the foreseeable future.

It is also necessary to develop a registry of cancer incidence among the military and compare the indicators with the general Ukrainian population.

Regular medical monitoring should be further provided to detect early manifestations of exposure to toxic substances through blood and urine tests for heavy metal concentrations in the body of military personnel.

So far, our study has shown that the use of trench candles was associated with a significant increase in the concentration of suspended particles within the range of ultrafine and some carcinogenic metals in the air, the impact of which on human health could be very harmful. Our examinations have revealed the maximum indoor air concentrations of suspended particles containing chromium, cadmium, and cobalt of 1712.71 μg/m^3 after only 10 minutes of the trench candle burning, which was 171.3 times higher than the WHO recommended air level of 10 μg/m^3 [36].

The use of trench candles during the Russian–Ukrainian war numbers in the thousands. Alongside mass smoking, this identifies the corresponding category at the high-risk population group and could increase the cancer incidence among the population of our country in a few years.

Unfortunately, people will overlook or tolerate the presence of air pollutants in low concentrations for a long time as they do not pose an imminent threat to their health.

The authors of the paper recognize that long-term prevention programs are hard to implement, and it is a challenge to provide all military personnel with protection against airborne suspended particles and chemical substances at the front line during high-intensity warfare. It should be noted, however, that the study on the impact of wartime carcinogens on the military and civilian Ukrainian population is extremely topical today and requires the development of a distinct primary and secondary program for prevention of oncological diseases at the present moment.

Conclusions

1. During the trench candle burning, suspended particles of various diameters, including nanoscale ones (from 11.5 nm to 365.2 nm), are released into the indoor air. The maximum particle number concentrations are detected at 1.5 meters above the floor level (breathing zone) 3–985 times exceeding background concentrations before the trench candle use.
2. The composition of ultrafine aerosol generated by the trench candle burning includes carcinogenic metals, according to the IARC classification (chromium, cadmium, and cobalt), in the nanoscale size range, that significantly increases the level of carcinogenic risk.
3. Extremely high concentrations of airborne suspended particles of different chemical composition emitted from the trench candle burning require the use of personal measures to protect the respiratory tract, eyes, and skin, as well as an efficient ventilation system should be used wherever available to reduce the levels of risk for public health impact.
4. Assessment of heavy metal load on the organism of military personnel and certain categories of civilian population, medical monitoring of their health and oncological screening should be built into the national cancer prevention program in Ukraine after the war.

Prospects for further research. In the future, it is planned to examine the presence of organic substances in the ultrafine aerosol from the trench candle (CO, polyaromatic hydrocarbon compounds) and detect the presence of hexavalent chromium, a known human carcinogen. Perhaps this will allow to revise the indications for lung cancer screening in some population groups, taking into account not only tobacco smoking risks, but also the facts of exposure to wartime carcinogenic air pollutants, including the duration of inhaling toxic smoke from trench candles.

Funding

The risk assessment of ultrafine aerosol from trench candles for developing cancer and other chronic diseases is part of the general scientific program “Cancer prevention and screening in the military and civilian Ukrainian population after the war” being developed by Zaporizhzhia State Medical and Pharmaceutical University.

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