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Involving schoolchildren in radon surveys by means of the "RadonTest" online system

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ABSTRACT

A 'citizen science' approach was evaluated as an approach to organize an extensive radon survey to be representative of the population of either single regions or a whole country. The "RadonTest" online system allowed schoolchildren to undertake and record short-term radon tests in their homes. Measurements were carried out in Israel using charcoal in miniature flacons and simple detectors with high sensitivity. Among other things, the "RadonTest" online system implements an alternative principle of building a radon map, allowing the display of radon tests more clearly than the traditional approach, while ensuring the confidentiality of test participants. Examples of public radon maps are presented, and the first test results are discussed. A scientifically based approach for the effective identification of buildings with a high radon concentration, based on the principle of radon regulation, is proposed.

1. Introduction

In many countries large scale and country-wide radon surveys are conducted to assess the impact of indoor radon on the population. The current situation with radon surveying in different countries and regions is briefly reviewed hereafter.

Since the indoor radon concentration has a lognormal distribution (Bossew, 2010), the main parameters of the radon potential hazard in common use are: (a) arithmetic mean (AM) of radon concentration in buildings - to estimate the average radon dose, and (b) geometric standard deviation (GSD), that characterizes dispersion of radon spatial distribution and allows estimating the inventory of buildings with radon above a reference level. An important condition for a reliable assessment of the AM and GSD is a representative sampling of buildings. The main requirements for representativity are: (i) the random sampling principle, and (ii) the distribution of measurement points in proportion to the population density.

These conditions and requirements are often not met, making it difficult to access radon impact on populations. In Israel, for example, the largest numbers of measurements were conducted in radon surveys in 1998 (1800 tests), 2007 (1318 tests), 2008 (1584 tests) and 2011 (1096 tests). A total of 14,100 tests (including 10,700 short-term and 3400 long-term ones) were performed in the years 1992–2001, while 25,000 tests were conducted in the period 1991–2012. However, the AM and GSD values obtained in different periods differ significantly, as shown in Fig. 1 (Tsapalov and Kovler, 2018b). This fact is primarily due to the absence of representative sampling. The representativeness is usually disturbed when commercial tests are ordered by building occupants, as occupants try to take measurements where they expect higher radon concentrations such as in basements, ground floors and rarely occupied residential protective rooms (RPRs). Typical RPRs are made of thick concrete slabs and walls, with an extremely airtight window and a steel door to be sealed when needed against chemical and biological attack. In addition, most commercial tests are conducted in radon-prone areas with an increased radon release from the soil. Therefore, the AM and GSD are significantly overestimated. Based on such measurements, it is impossible to provide a reliable estimation of the impact of radon on the population in order to compare risks and, consequently, to take adequate necessary actions at the national level.

The problem of the reliability of the AM and GSD assessment is

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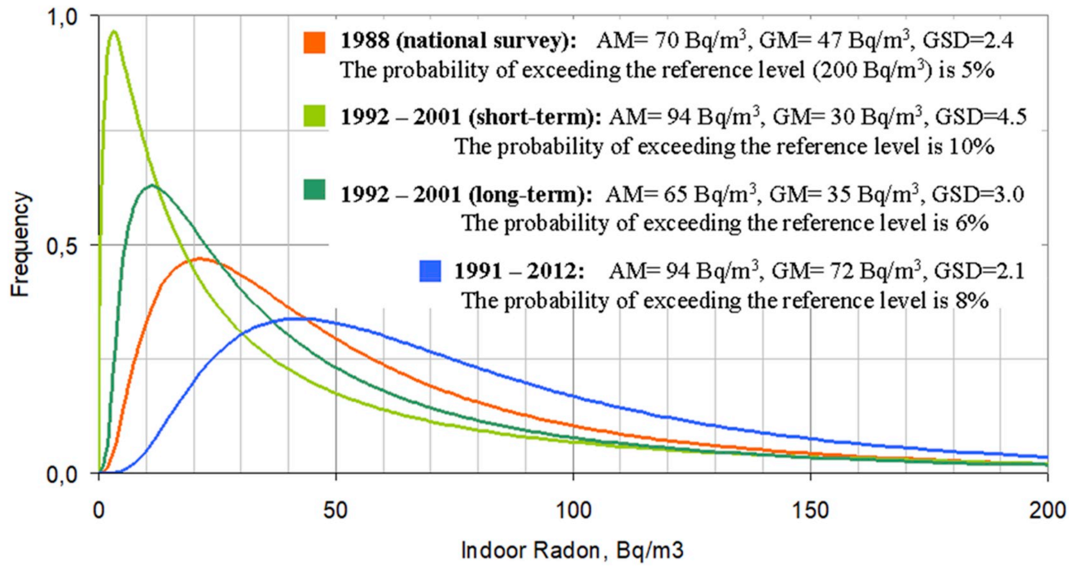

Fig. 1. Indoor radon distributions in Israel based on the results of surveys in different years.

relevant for all countries where mass radon surveys have been conducted. For example, recently the Radon Map of European countries has been published on the Web.[1] However, according to Cinelli et al. (2019), the data array at the base of this map does not allow assessing the risk of exposure to radon for either a particular country or the population of the EU - due to the lack of a representative sample of buildings and test rooms. Most of the radon tests were carried out in basements and on the ground floors.

Another problem of radon surveys and building radon maps on their basis, in our opinion, is the principle of building the maps accepted in the USA and the EU. The basis of this principle (Cinelli et al., 2019), which has already become traditional, is the division of the territory into equal squares of 10 × 10 km of different colors. The color of the square corresponds to a certain range of the average level of indoor radon, calculated from the results of all tests inside the square. Firstly, such a map displays the average geogenic radon potential in a certain square and does not give information about the spatial distribution of indoor radon, as well as its extreme values inside the square. Secondly, the uncertainty of the geogenic radon potential varies considerably between the squares, since only 2–4 tests can be carried out in one square, while more than 1000 tests - in another square. Therefore, there is a need to display an additional map with the number of tests in each square. This way of displaying test results is understandable for professionals, however, it may be unclear to the general public searching for information about local radon hazards.

Extremely important, but so far unresolved, is the problem of comparing the test results with the reference level. It is due to the fact that when assessing the uncertainty of the test result, the temporal variations of indoor radon are not taken into account quantitatively. Instead, only instrumental uncertainty is quantified, which, however, is significantly lower and does not play a role in case of short-term tests. Despite the fact that mass radon tests are carried out for tens of years (for example, for almost 30 years in the USA), there is still no metrological support of compliance criterion of the tested room to the requirements of safety and radon mitigation. In the US standards (Environmental Protection Agency, 1993; Environmental Protection Agency (1997); ANSI/AARST MAH (2014), such a criterion was gradually refined with increasing practical experience, but it still does not have a clear scientific justification behind. This problem is discussed in more detail in the paper (Tsapalov and Kovler, 2018a), which proposes a simple, but quite reliable and scientifically justified principle of indoor radon regulation.

The current study uses a citizen science approach for data collection, in which the public (in this case school students) assist scientists in their scientific research. The ENVIRAD project in Italy effectively involved schoolchildren in radon surveys providing good scientific results and increased student engagement (Esposito et al., 2005). This approach provides benefit for both scientists (e.g., scientific information) and students involved (e.g., learning outcomes, such as, scientific literacy and statistical literacy), and has been executed successfully in many scientific domains such as ecology, astronomy, statistics, etc. (Ben-Zvi et al., 2012; Garfield and Ben-Zvi, 2008; Golumbic et al., 2019; Sagy et al., 2019).

Evaluating citizen science learning outcomes among participating students reveals an increase in learning and understanding of the scientific research process, as perceived by project guides and teachers (Kountoupes and Oberhauser, 2008; Silva et al., 2016). Students were also found to learn new scientific content, relevant to environmental ecosystem structures and functions, and learn about the complexity of social-ecological system (Ballard et al., 2017; Golumbic et al., 2016).

2. Organization of indoor radon surveys using a citizen science approach

2.1. General

To implement the radon survey in Israel involving schoolchildren, the following actions were required:

- participation of researchers from the Technion as project initiators[2] supported by the European Commission in the framework of the “RadonACCURACY” grant,
- permission from the Israeli Ministry of Education to attend schoolchildren in a survey,[3] subject to the consent of their parents and the protection of personal data,
- participation of the Taking Citizen Science to School (TCSS) Center[4] as a communicator between representatives of the educational system and the Technion team,

[1] https://remap.jrc.ec.europa.eu/.

[2] https://nbri.net.technion.ac.il/en/radon-project/.

[3] https://nbri.net.technion.ac.il/files/2019/04/Ministry-of-Education.pdf.

[4] https://www.tcss.center.

– development of the recommendations for teachers on the distribution and exposure the samples for indoor radon measurements,
– development of the "RadonTest Online Data Collection and Analysis System" ("RadonTest" online system) for conducting mass measurements of indoor radon based on a special mobile application associated with a laboratory database via a website,
– selecting the miniature charcoal flacons for passive sampling and labeling them with QR-code that is scanned by a mobile phone to access the website,
– logistics support.

Involving schoolchildren in the radon tests in their homes seems to be an effective instrument, since the dwellings to be covered correspond to both conditions of the survey: (i) a better compliance to the random sampling principle, and (ii) the distribution of measurement points in proportion to the population density. In addition, middle and high school students are quite capable of recording test conditions using the mobile application and simple sensors. Moreover, the participation of schoolchildren was incorporated into the school curriculum.

The current radon survey in Israel uses a citizen science approach for data collection, in which the public (in this case school students) assist radon experts from the Technion in their research endeavors. The involvement of the schoolchildren was enabled due to the active participation of the TCSS team from the Technion and the University of Haifa.

The recommendations for sampling are important to ensure representative sampling. This document used can be found at the link.[5] The most important recommendation was to conduct radon tests in bedrooms, where the occupants spend most of their in-house time. Usually the radon levels in basements and sealed shelters are higher than in the living zone, however those rooms are rarely occupied. Therefore, the radon test in the basement or shelter, which is not a bedroom, should not be carried out. A failure to follow this recommendation will reduce the representativeness of the sample, and lead to an overestimate of the AM and GSD. This issue is also discussed in Section 3.

2.2. Short-term method of radon adsorption in activated charcoal

The short-term method of radon adsorption in activated charcoal allows many measurements of indoor radon at the lowest cost and least time. More than 23,000,000 short-term indoor radon tests have been conducted in the US (George, 2015). The scientific rationale of this approach is provided by Tsapalov and Kovler (2018a), including the dependence of the coefficient of radon temporal variation on the test duration. It is important to note temporal variation is significantly greater than instrumental uncertainty for short-term methods, so that there is no need to measure radon with high precision. However, in relatively rare cases long-term tests should be conducted if the result of assessment based on a short-term test exceeds a reference level, considering the uncertainty due to temporal variation of indoor radon (Tsapalov and Kovler, 2018a).

The method uses passive sampling with activated charcoal. The measurement procedure consists of the five steps: (a) regeneration of the activated charcoal at the temperature about 150 °C, (b) preparation of the samples, which includes weighing and packaging the charcoal flacon into a package labeled by the QR-code, (c) passive exposure of the charcoal flacons from 3 to 6 days, (d) measurement of the activity of radon adsorbed by the charcoal, and (e) calculation of the radon concentration considering the sampling conditions. Exposed charcoal can be reused after regeneration.

We have developed (Tsapalov, 1999) and use for passive exposure the miniature (about 20 mL) charcoal flacon type CF-13, as shown in Fig. 2. The flacon contains about 13 mL of granular activated charcoal. The equivalent adsorption volume of the CF-13 varies from about 10 to 20 L of air, depending on the duration of exposure and air humidity. The effect of air humidity is taken into account by determining the increase in the mass of the flacon over the test period.

In addition, we use for the measurement of radon activity in charcoal the miniature detector type BDB-13 as shown in Fig. 2 based on a gas discharge counter. For activity measurements, the charcoal is emptied from the CF-13 into the detector. The detector connects to the unit with a WiFi channel. Thus, all the detectors in the laboratory are controlled using the interface integrated into the "RadonTest" online system via the Web and WiFi. Metrological checking the detector type BDB-13 together with the charcoal flacon type CF-13 at different radon concentrations and exposure duration showed that the uncertainty of this method does not exceed 25%.[6] In the case of measuring low (zero) radon concentration, the uncertainty of the method can be significantly higher, but this does not affect the reliability of the comparison of the test result with the reference level. For example, this detector with the CF-13 ensures the measurement uncertainty of indoor radon is about 12 (or 16) Bq/m^3 at zero radon level, if the duration of activity measurement is about 1 (or 0.5) hour and exposure time is about 4 days.

2.3. How "RadonTest" online system works

Before indoor radon tests, the number of the charcoal flacon, as well as the corresponding number on the label with the QR-code (see Fig. 2) and initial mass of the CF-13, are registered in the "RadonTest" online system in the Technion lab. Then a box containing 40–80 prepared samples is transferred to the school.

Scanning QR codes allows to identify the sampler, the geolocation of the test object, the start and the end of sampling. In addition to the detailed sampling guide, the mobile application includes a questionnaire for collecting information about building characteristics and testing room, as shown in Fig. 3.

Our experience shows that the use of the mobile application is not difficult, even for schoolchildren. Thus, sampling and registration of the test conditions can be successfully performed without involving professionals; guidance by the students' teachers and the TCSS team would be sufficient. After returning the exposed samples to the Technion lab, the professionals perform their identification and measure the radon

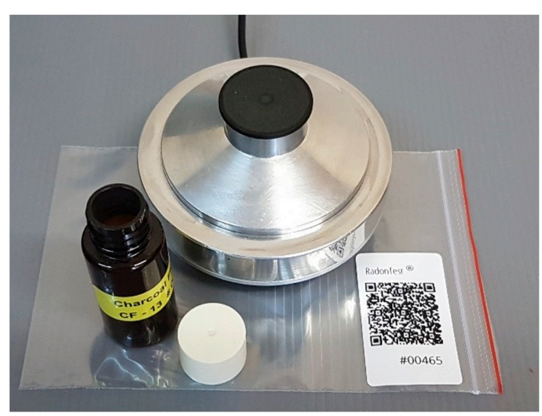

Fig. 2. Equipment for measuring indoor radon using the charcoal method consisting of (a) the BDB-13 detector and (b) several samples (usually 20–40), each sample includes the CF-13 charcoal flacon and the package labeled with the QR-code.

[5] https://nbri.net.technion.ac.il/files/2019/04/Recommendations-and-Guide.pdf.

[6] https://nbri.net.technion.ac.il/files/2019/04/Radon-Survey-in-Israel_2019.pdf.

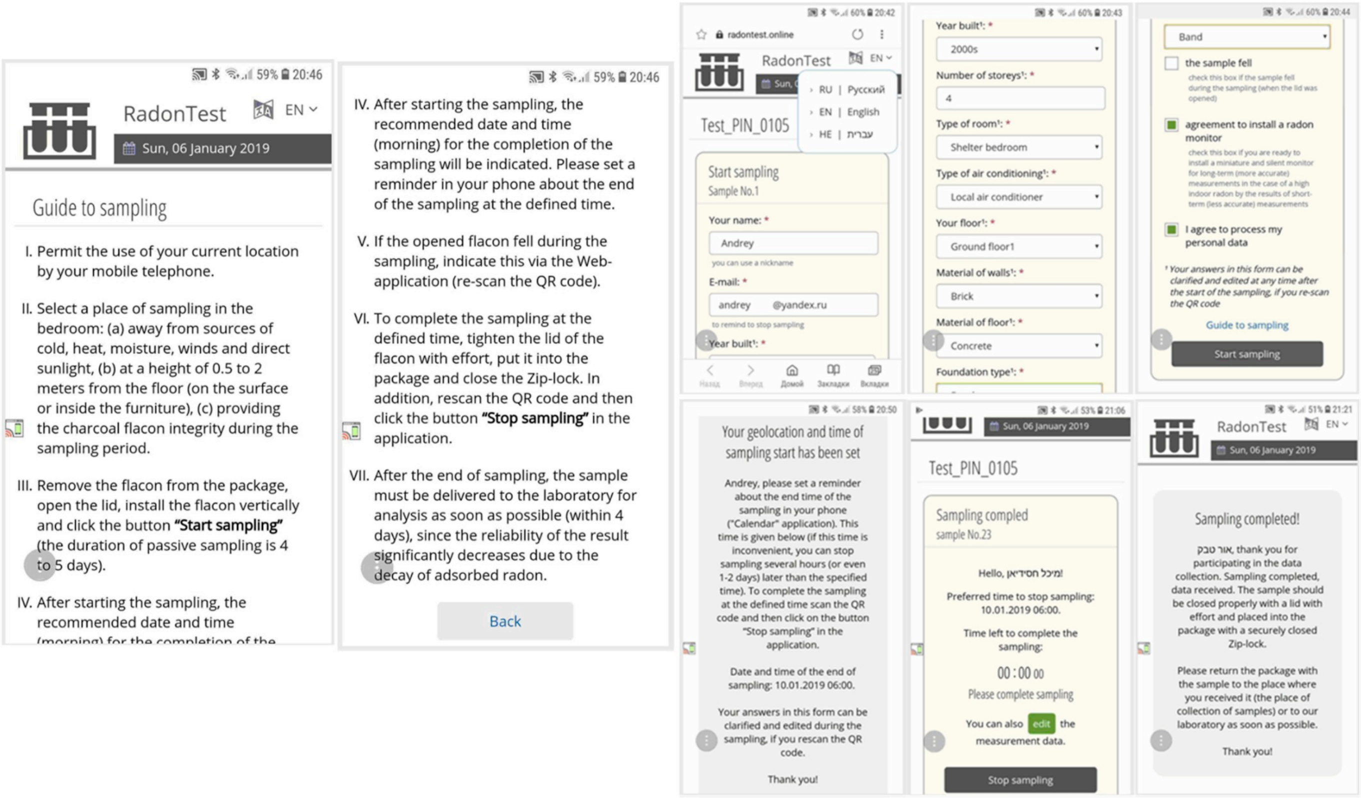

Fig. 3. The mobile application including Guide to sampling and Questionnaire, and the most important messages after the start and stop of sampling (English version).

activity in the charcoal flacons. The measurement results are stored in a secure database and displayed on the Radon Map.

The "RadonTest" online system[7] is a cloud service available for use anywhere in the world, which allows to organize the work of laboratories in a single information space, and to monitor the data keepers and actions of all participants of radon tests. Therefore, this system can be used in different laboratories and in any country. In addition, the system can serve the most common radon measurement methods (charcoal, electrets, SSNTD and continuous measurements) provided with appropriate sampling guide translated into different languages in the mobile application.

3. Results and discussion

Initially, indoor radon measurements were carried out in the dwellings of Technion employees and students in Haifa. After the approval of the Ministry of Education (January 2019), radon tests began to be conducted in the dwellings of schoolchildren throughout Israel. Thus, before the beginning of the summer (school holidays), about 400 short-term radon tests were made in different regions of Israel as shown in the Radon Map (see Fig. 4).

The test results are displayed in the public Radon Map[8] as markers in the form of circles with a diameter of about 120 m at the maximum scale of the map in order to maintain anonymity of the test participants. The colors of the markers correspond to the radon concentration scale, which is shown below the map. In addition, each marker contains the information about indoor radon concentration (the most probable value and instrumental uncertainty) for the test period, as well as the duration and date of the test start. Thus, the constructed Radon Map does not contain any personal data, but at the same time displays the spatial distribution of radon in buildings and its extreme values. This way of displaying test results contains more information and is also more understandable to test participants, their neighbors, and any interested people. It is important to note that the building of such a map is carried out automatically by the "RadonTest" online system not only in Israel, but also on a global scale. Based on these data, it is also possible to build professional radon maps, as mentioned in the introduction. The spatial distribution of the results of short-term indoor radon tests corresponds to the lognormal law, as shown in Fig. 5 with the following validated (unvalidated) characteristics: AM = 41.8 (45.4) Bq/m^3, GM = 25.5 (26.4) Bq/m^3 and GSD = 2.70 (2.83).

The need to validate (delete or edit) test results was due to the fact that the highest levels of radon (4 tests with values greater than 500 Bq/m^3) were found in hermetically sealed unoccupied shelters, which was a failure to meet the guidelines (see Section 2.3), so these 4 tests were removed from the validated data set. We later found out that these 4 cases are the initiative of the schoolchildren themselves (or their parents), therefore the TCSS team will make efforts to eliminate deviations from the specified sampling conditions in future tests.

In addition, detailed surveys of buildings with abnormally high levels of radon in sealed shelters and basements showed that the radon concentration in the residential area (living rooms and bedrooms) is not high. Therefore, summarizing this and previously accumulated experience, we recommend taking measurements, first of all, in the bedrooms where the occupants spend most of their time.

Another important task for the further development of this study is to expand the number of involved schools, the location of which should cover the entire territory of Israel in proportion to the population density. This expansion should include a validation of the concept that citizen science gives a representative sampling.

Fulfillment of these conditions will provide a representative sample of buildings and a reliable assessment of the impact of radon on the

[7] https://radontest.online.
[8] https://radonmap.online/indoorradon/.

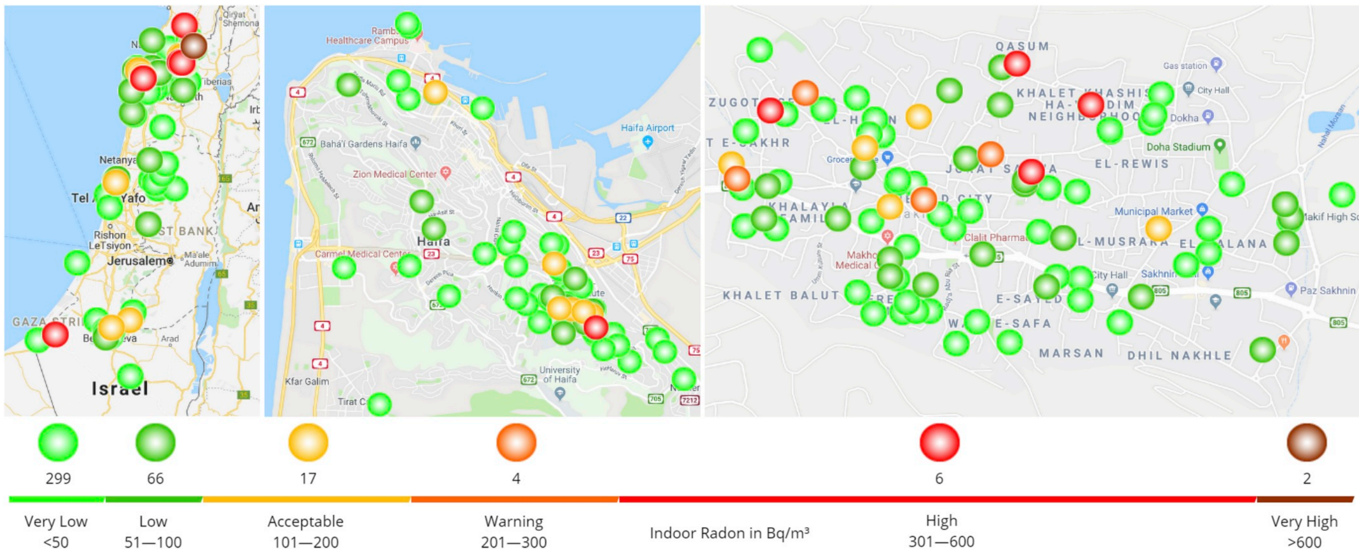

Fig. 4. Fragments of the public Radon Map with test results in Israel (Dec.2018–May 2019).

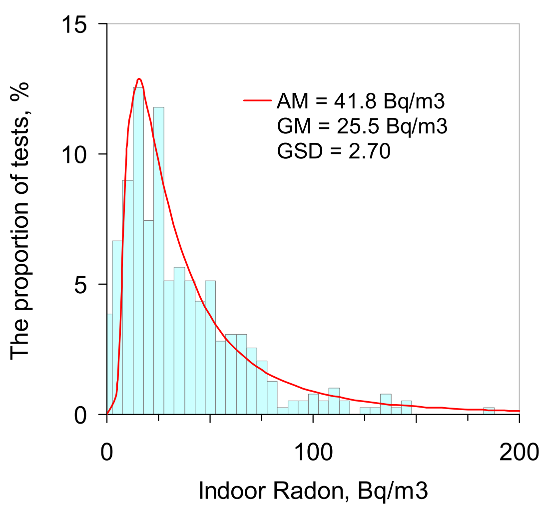

Fig. 5. Indoor radon distribution in Israel based on the survey in Dec. 2018–May 2019.

Israeli population with the minimum required number of tests. How many tests are required? The results of a Monte Carlo simulation method in the case of a representative sample of buildings showed (Tsapalov and Kovler, 2018b) that the AM uncertainty (assuming the absence of seasonal indoor radon variations):

(i) does not exceed 10% or 5%, if the number of tests is at least 1000 or 5000, respectively, regardless of the nature of the lognormal distribution of indoor radon,
(ii) does not depend on the duration of tests, if their number exceeds 1000, and GSD>1.8.

Since we use short-term tests, in order to take the seasonal factor into account, it is necessary to repeat measurements in different seasons of the year in the same area. Perhaps the effect of the seasonal factor in Israel is insignificant. Nevertheless, taking into account the repeated measurements, it would be necessary to conduct totally 2000–3000 tests, which, according to our estimates, will take about 2–3 years, if the collaboration with schools is continued.

Thus, we assume that a reliable estimate of radon risk in Israel can be obtained at a low cost over a period of several years. Note that even with a relatively low national average of indoor radon, there are still thousands of buildings with radon concentrations above the reference level - because of the lognormal character of its spatial distribution (Fig. 5). The number of such buildings can be estimated with the known values of AM and GSD. However, the question arises - how to locate all these buildings? To solve this problem, we suggest implementing the same approach, which is based on the participation of schoolchildren, but with the difference that older schoolchildren could perform not only sampling in their homes, but also carry out measurements of radon activity in charcoal under the guidance of their teachers during the laboratory lesson in the school. The organization of such laboratory lessons is facilitated by the "RadonTest" online system and the simple user-friendly and cost-effective charcoal method described in Section 2.4. This approach will significantly increase the number of tests per year, and at the same time will reduce the cost of the entire radon survey.

As already discussed in the introduction, there is still no generally accepted quantitative criterion for comparing the test results with the reference level in order to make a reliable decision on the compliance of the tested room with radon safety requirements and the need for mitigation. In this regard, we offer the scientifically justified criterion (Tsapalov and Kovler, 2018a), which in the case of short-term tests looks simple enough. According to the regulation principle,[9] the annual average indoor radon concentration will not exceed the reference level in the short-term test, if the following condition is met:

$$C(t)\cdot[1+K_V(t)] < C_{RL} \tag{1}$$

where

$C(t)$ is the result of measuring the radon concentration during the test (Bq/m^3),
C_{RL} is the reference level (Bq/m^3),
$K_V(t)$ is the coefficient of temporal radon variation, or the temporal radon uncertainty (rel).

The values of the $K_V(t)$ depending on the test duration and measurement mode are given in Tsapalov and Kovler. (2018a). For example, $K_V(t) = 1.25$, if the test duration is about 4 days.

If the condition (1) is not met, it is necessary to repeat the test with a measurement duration of at least 8 months or perform two tests at

[9] https://nbri.net.technion.ac.il/files/2019/04/Tsapalov_Kovler_Indoor-radon-regulation_JENVRAD183_2018.pdf.

different seasons of the year for at least 2 months each (the interval between measurements should be 4–8 months) using suitable measurement methods. Alternatively, four short-term tests are allowed in different seasons of the year. These validating tests should be carried out with the participation of professionals.

We hope that we will have the opportunity to continue measurements for several more years and collect a statistically significant number of short-term radon test results to conduct an adequate statistical analysis. This will allow validation of the simulation results, as well as assessment of the representativeness of the sample of buildings with the participation of students. This approach was made possible only thanks to the innovative "RadonTest" online system. Obviously, the combination of this approach in organizing mass measurements with the principle of regulating indoor radon (1) makes it possible to most effectively identify buildings with an increased level of radon. However, as the recently published IAEA recommendation (IAEA, 2019) shows, this simple and reliable principle is still waiting for the proper professional discussion.

4. Conclusions

The radon survey in Israel involving schoolchildren in citizen science by means of the "RadonTest" online system using the charcoal method was conducted for the first time. This experience seems to be quite successful. Therefore, the radon survey in Israel will continue and develop to reliably assess the impact of radon on the population, as well as to identify buildings with elevated radon levels. We are confident that such an organization of mass radon survey, utilizing citizen science concepts, is most effective in terms of time and costs in other countries or single regions. In addition, the involvement of schoolchildren is an important educational process, which contributes to the wide and rapid dissemination of information about the risks from radon among the population and administrations of different levels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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