ORIGINAL PAPER

Verification of correction factors for determining mean annual levels of radon in underground facilities

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Abstract The first verification of a tool developed to improve the work of controlling bodies, managers and employees of underground facilities subject to radiation protection requirements was conducted. The recommended values of correction factors were verified using archival results of measurements conducted for the Institute of Occupational Medicine in Łódź in seven underground workplaces in Poland over exposure periods of a month (10,8678 data) and a quarter of a year (53,688 data). In a cave two groups of monthly factors, produced estimates with almost 70% to 99% consistency with the measured values. Along tourist routes located in mines, a similar fit was obtained using three groups of correction factors for measurement results from March, June and July. In the extraction areas of active underground mines, the best fit was produced by factors calculated as averages for spaces varying in the degree of insulation and ventilation method, while in other departments of mining plants, by correction factors recommended for facilities equipped with mechanical ventilation systems. All the quarterly correction factors produced the best fit between estimated mean annual concentrations and measurement results obtained in the second quarter of the calendar year. A wide variation in result consistency (from 20–30 to 65–80%) obtained for two underground tourist routes in the fourth quarter of the year demonstrates that it is best not to adopt results from this measurement period (October-December) for estimating mean annual radon concentration using the set of quarterly correction factors.

Keywords Monthly and quarterly correction factors · Radiology database · Mean annual radon concentration · Underground facilities · Workplaces

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Introduction

In Poland, provisions concerning radon in workplaces are regulated by an amendment to radiological protection laws (Law 2000; Directive 2013). In 2019, the reference level of radioactive radon in the air of workplaces was defined as 300 Bq/m^3 (Article 23b of the Law Journal of Laws 2023 item 1173 consolidated text). The responsibility for conducting measurements necessary for determining the mean annual value of radon concentration rests with the head of the entity carrying out business activity (Art. 23c of the Law 2000). In the case of workplaces located in areas where mean annual radioactive concentration of radon may exceed the

reference level in a significant number of buildings, legislation specifies the location of these workplaces (on the ground floor or at basement level) and the character of their activity (related to groundwater treatment). A list of workplaces exposed to increased radon concentrations, in addition to those specified by Article 23 of the Atomic Law, has been published in the National Action Plan for Long-Term Risks of Radon Exposure in Buildings and Workplaces (Minister of Health Announcement 2021). Apart for defining a duty to conduct measurements of radon concentration, the law obliges entity heads (employers) to optimise the exposure of employees working in such conditions, and in the event of an exceedance of the level of 300 Bq/m^3 a year, to take measures ensuring the reduction of workers' exposure to radon. In Poland, radon measurements in workplaces can be performed by accredited dosimetry laboratories (5 centres in total) and conditionally (until the end of 2023), laboratories which have obtained satisfactory results in intercomparison measurements organized by the Chief Sanitary Inspector (GIS). Soon, such limited technical backup may become an obstacle to providing reliable measurement results, which are subject to strict control by regional GIS units.

A partial solution, but available for quick implementation, is assessment of mean annual levels of radon concentration in workplaces by using correction factors calculated for one-month and three-month (quarter) measurement periods. They have been developed in compliance with the Chief Sanitary Inspector (GIS) guidelines and the provisions of the National Action Plan (Minister of Health Announcement of 22 January 2021 Item 169) by employees of Wrocław University of Science and Technology (Fijałkowska-Lichwa & Przylibski, 2022). The solution, enabling estimation of mean annual values of radon concentration in various types of underground facilities, was developed on the basis of more than 440,000 radon concentrations registered at 1-h intervals in several well-known underground workplaces in the Sudetes. Based on their analyses, the researchers created a database of monthly (k_{1m}) and quarterly (k_{3m}) correction factors recommended for use in many countries in Europe and worldwide located in zones of temperate climate with continental-to-oceanic (marine) transition, with four distinct seasons, i.e. spring, summer, autumn and winter.

In their study, Fijałkowska-Lichwa and Przylibski (2022) demonstrated relationships between the ranges of variation in estimated correction factors k_{1m} and k_{3m} and individual characteristics of underground facilities such as air exchange method and the extent to which their interiors are insulated from the atmosphere. As a result, they grouped the correction factors by matching them to facilities without a specified ventilation method and those with mechanical and natural ventilation, including spaces well insulated from the atmosphere. Fijałkowska-Lichwa and Przylibski (2022) emphasized that the estimation accuracy of mean annual levels of radon concentration in underground facilities depends on the adopted type of correction factor (k_{1m} or k_{3m}). They recommended using monthly correction factors (k_{1m}) for determining mean annual concentration in facilities with natural air exchange and quarterly factors (k_{3m}) for mechanically ventilated spaces. They specified the value range of k_{1m} factors (from 1.2 to 3.3) for the first group between January and March and between October and December. In the other months of the calendar year, k_{1m} stays in the range of 0.6 to 0.8. In facilities with undisturbed natural indoor-outdoor air exchange, k_{1m} varies from 1.0 to 1.5 between January and March and between September and December, and from 0.7 to 0.8 between May and September. In April, it takes the value of 1.0. For facilities with mechanical ventilation, k_{3m} is characterized by values in the range 1.3–1.4 in the first and the fourth quarter of the year, and of 0.9 in the second and the third quarter. In facilities with unknown ventilation methods or when mixed-mode ventilation is used, Fijałkowska-Lichwa and Przylibski (2022) suggested using mean values. For k_{1m} they range $\geq$ 1.0–1.6 (from January to March and from September to December) and < 1.0–0.7 from April to November. For k_{3m} they range 1.3–1.4 (in the first and the fourth quarter), and equal 0.9 (in the second and the third quarter). The results of Fijałkowska-Lichwa's and Przylibski's analyses (2022) show that the best consistency of estimated and measured mean annual values are obtained based on correction factors estimated in March (over 60%), August (over 70%) and September (even over 80%), and the worst—based on data collected between October and December. Such results have confirmed that the accuracy of correction factors, both for monthly and quarterly exposures, is much higher in periods of increased radon activity

concentration. Such conclusions have explicitly underscored the relevance of the proposed solution for broadly defined radiological protection.

In view of the need to determine the mean annual level of radon concentration for initial assessment of occupational exposure risk, the authors went on to verify the solution proposed by Fijałkowska-Lichwa and Przylibski (2022). The rationale behind and the need for such analyses lie in the fact that so far it has been the only alternative solution described in Polish and world literature to streamline the time-consuming measurement process, facilitate corrective decisions and recommend strategic remedial actions aimed at keeping radon concentrations in underground workplaces at a safe level of 300 Bq/m^3. The authors believe that the alternative solution proposed by Fijałkowska-Lichwa and Przylibski (2022) can be regarded as a good practice relating to methods and techniques of recognizing the first signs of risk of occupational exposure to radon and its short-lived progeny.

So far, databases of correction factors available in literature have been compiled only for dwellings in Poland (Kozak et al., 2011), Ireland (Burke & Murphy, 2011), and Great Britain (Gillmore et al., 2005; Groves-Kirby et al., 2015), in South Korea (Park et al., 2018), several provinces in Canada (Krewski et al., 2005), Pakistan (Rahman et al., 2007) and Slovakia (Müllerová et al., 2022). It is still just a fraction of all places in the world at risk of increased exposure to radon and its short-lived daughters.

Material and methods

To carry out their research task, the authors used a database of archival radiology data from an accredited dosimetry laboratory at the Institute of Occupational Medicine in Łódź with accreditation No. AB 327 of the Polish Center for Accreditation for radon (Rn-222) activity concentration measurements made in any range of time exposure by track detectors (20–4300 kBq•h•m^{-3}).

These are the results of radon concentration measurements conducted in workplaces between 1995 and 2012, partly published in Polish research papers (Olszewski, 2006; Olszewski et. al. 2010, 2015) and international publications (Olszewski et al., 2005; Walczak et al., 2017). The workplaces chosen for this study satisfy Fijałkowska-Lichwa's and Przylibski's (2022) criteria concerning the ventilation method and the degree of insulation from the atmosphere. A new aspect is the work time schedule. In the case of tourist routes, work was done from 9 a.m. to 6 p.m. 7 days a week (it was shortened in autumn and winter). As for the mining plants, work was performed in a four-on four-off shift pattern seven days a week, except a total of 2–5 days a year at Christmas, Easter and on public holidays.

Measurements in underground tourist facilities were conducted in accordance with recommendations issued by the International Commission on Radiation Protection (ICRP 2011, 2014, 2017), the International Atomic Energy Agency (IAEA 2014), the International Radon Measurement Association (IRMA 2017), and the Chief Sanitary Inspectorate (GIS) in Poland (Report 2021). The measurements were conducted using track detectors with a diffusion chamber. The number of used CR-39 track detectors varied as it was adjusted individually to the surface areas of the spaces housing particular workplaces. The detectors were spaced evenly in places occupied by employees, surveillance staff or service workers for at least 4 h a day. Measurements were also carried out in mine chambers, machine rooms, welfare facilities such as bathrooms or changing rooms, reception areas, corridors and entrance/exit halls in tourist facilities located on the ground floor or at basement level. In such places, there was a risk of sizeable radon ingress, and employees occupied them for at least 50 h a year, i.e. about 1 h a week. Along tourist routes, detectors were placed at a height of the breathing zone (1.5 to 2 m above the floor) at places of longer stops representative of the whole space.

In active mining plants, radon concentration was measured using a method consistent with an original methodology for assessing radiation exposure developed entirely by employees of the Radioactive Contamination Department of the Institute of Occupational Medicine in Łódź. The basic tool for measuring radon concentration in underground mines was the track detector LR-115 by French manufacturer Kodak Pathe placed in an open cassette type OC-1, which was mounted directly on mining helmets. It is the so-called HCS system (Helmet Cassette System) based on employees wearing helmets with the cassettes (sealed after the insertion of a detector to prevent unauthorised opening) for

a determined exposure time. A detailed description of the measurement system and the dosimetric technique of reading track density from the detector has been provided by Domański et al., (1981).

The method of estimating mean annual values of radon concentration used by the authors was identical to the assumptions presented by Fijałkowska-Lichwa and Przylibski (2022). Two relations were used to determine the mean annual concentration. For measurements in one-month exposure, the mean annual value of radon concentration was estimated using Eq. (1), and for 3-month (quarterly) exposure—according to relation 2:

$$C_{Rn} = k_{1m} \cdot C_{1mRn} \tag{1}$$

where C_{Rn} is the mean annual activity concentration expressed in Bq/m^3, k_{1m} is the correction factor for the month of the exposure, C_{1mRn} is the mean monthly value of ^{222}Rn activity concentration expressed in Bq/m^3, and

$$ = k_{3m} \cdot C_3 \tag{2}$$

where k_{3m} is the correction factor for three month exposure, and C_{3mRn} is the mean value of ^{222}Rn activity concentration for a quarter of a year, expressed in Bq/m^3.

The mean annual value was estimated for four groups of monthly correction factors in four underground facilities and for three groups of quarterly correction factors in three underground facilities (Table 1, Fig. 1).

Results and discussion

The estimation accuracy of mean annual radon concentrations calculated using four groups of monthly

Table 1 Overview of correction factors: 4 monthly groups (a) and 3 quarterly groups (b) Authors' own work based on Fijałkowska-Lichwa and Przylibski (4)

Time of exposure	k_{1ma}—for naturally ventilated facilities well insulated from the atmosphere	k_{1mb}—for non-insulated facilities	k_{1mc}—averaged for underground facilities	k_{1md}—for facilities with mechanical ventilation system
Month (a)				
January	3.34	1.41	1.52	0.73
February	2.80	1.38	1.42	0.38
March	1.56	1.19	1.16	0.52
April	0.55	0.96	0.88	0.40
May	0.83	0.77	0.74	0.40
June	0.60	0.71	0.70	0.73
July	0.70	0.71	0.81	1.76
August	0.56	0.69	0.78	1.80
September	0.63	0.83	0.95	2.40
October	1.40	1.00	1.10	1.20
November	1.20	1.30	1.30	1.60
December	2.70	1.50	1.60	1.60
Quarter (b)	k_{3ma}—for naturally ventilated facilities	k_{3mb}—for facilities with a mechanical ventilation system	k_{3mc}—averaged for all underground facilities	
No. 1	0.62	1.40	1.32	
No. 2	0.76	0.81	0.90	
No. 3	2.14	0.72	0.87	
No. 4	1.96	1.31	1.37	

correction factors was verified with data obtained from measurements conducted for many years in the cave, a former mine operating as an underground tourist route, in two active copper mines and one disused (since 2020) zinc and lead mine (Fig. 1). The correction factor k_{1md} was excluded from analyses conducted for the cave because of its lack of mechanical ventilation. The fitting accuracy of quarterly factors was checked against the results of radon measurements conducted in the workings of a former mine used as a tourist route and a radon inhalatorium, and in a tourist-accessible former military facility in the Sudetes. A list of the groups of correction factors used in the comparative analyses is provided in Table 1.

One-month data

Verification of Fijałkowska-Lichwa's and Przylibski's (2022) assumptions started with organising measurement data in one-month intervals. The mean values obtained for successive months were converted according to Eq. 1 using monthly correction factors (Tab. 1a) for: naturally ventilated spaces well insulated from the atmosphere (k_{1ma}), naturally ventilated spaces without insulation (k_{1mb}) and all facilities in total (k_{1mc}). Data analysis was performed using measurement results from 865 points. On the basis of nearly 10 years of measurements, the mean annual value of radon concentration in the cave was calculated as 2034 Bq/m^3. The values of radon concentration in the cave estimated by using monthly correction factors varied (Fig. 2). The best fit to the annual average was obtained in the cave using correction factors k_{1mb} and k_{1mc} throughout all calendar year. At the same time, correction factors k_{1ma} produced comparable results only in November and May. The mean annual values of radon concentration estimated on the basis of measurements in the indicated months differed by less than 10% compared to the value determined using the other two groups of factors and the value resulting from measurements. The lowest accuracy compared to the mean measured annual concentration was obtained in the cave using the k_{1ma} factor in October and between December and February. In this period, the estimated mean annual concentration differed by 40% to even more than 160% from the value obtained from measurements (Fig. 2).

The same kind of analysis was conducted for the correction factors k_{1m} used to calculate the mean annual radon concentration in an underground tourist route operating in a former mine in Złoty Stok. The analyses comprised measurement results from 90 measurement points. On the basis of measurements conducted between September 2004 and January 2006, the mean annual concentration of radon in the whole facility was determined to be 1434 Bq/m^3. The mean annual values of radon concentration estimated by using monthly correction factors varied (Fig. 3). The best fit of the estimated value to the mean annual value derived from measurements was observed in March, May, June and July for three k_{1m} correction factors: k_{1ma}, k_{1mb}, and k_{1mc}. In these months, the estimated values differed by < 10% to 30% from the mean annual value derived from measurements. The worst fit of the estimated value was obtained in October and November for all the four groups of k_{1m} correction factors (Fig. 3). The k_{1md} correction factors were characterized by a much lower fit. In February, March, April, May, August, and November, the estimated annual means differed by two and even four times from the values calculated using the other three groups of factors (Fig. 3). A comparable degree of fit for all correction factors was observed in December and June (Fig. 3).

Analyses verifying the k_{1m} correction factors recommended for determining the mean annual value of radon concentration were also conducted in the workings of metal ore mines. In total, these were 4 divisions of a copper mining company and 9 divisions of a zinc and lead mine. In both cases, mean annual values were determined using k_{1md} correction factors for underground facilities equipped with a mechanical ventilation system, and k_{1mc} factors, calculated as averages, for all underground facilities. The estimations were based on 1-month measurements conducted in the copper mining company in February 2012, and in the zinc and lead mining company—in December 2006. Based on environmental dosimetry measurements conducted on a group of 4254 employees of copper mine No. 1 and 3037 employees of mine No. 2 (including 1228 employees in the main area, 1092 in the eastern area, and 717 in the western area of mine No. 2), and 1312 employees of the zinc and lead mining company (including 402 in mine No. 1, 45 in mine No. 3, 444 in mine No. 6, 53 in mine No.

> 200 - 500 Bq/m^3

> 500 Bq/m^3

> 1000 - 3000 Bq/m^3

1 – monthly exposure, 3 – quarterly exposure

8, 64 in mine No. 9, 113 in the mining and shaft works department, 40 in the electrical department, 38 in the mechanical department, 77 in the shaft and heavy machinery depot and 36 in the ventilation department), mean annual concentrations of radon in each of these plants were determined. For the copper mines these were: 484 Bq/m^3 (mine No.1), and 420 Bq/m^3 (mine No. 2). For the zinc and lead mining plant it was 857 Bq/m^3.

After applying the k_{1m} correction factors, it turned out that the best fits were obtained in the mechanical department, mine No. 9 and mine No. 1 of the zinc and lead mining plant (even 90% consistency of results). In copper mine No. 1, the consistency

◄**Fig. 1** Location of selected underground facilities on a digital administrative map of Poland prepared by the Head Office of Geodesy and Cartography (GUGiK) on the basis of the General Geographic Objects Database available on Statistics Poland website (https://stat.gov.pl/statystyka-regionalna/jednostki-terytorialne/podzial-administracyjny-polski/?pdf=1) with indicated mean annual values of radon concentration determined on the basis of radiation measurements conducted from 1995 to 2012 for the Institute of Occupational Medicine in Łódź (Authors' own work). Explanation: ZG—copper mining plants, I, II—mining regions, ZL—zinc-and-lead mining plant, K—inhalatorium and tourist rote in Kowary, O- military facility Osówka, JN—Niedźwiedzia (Bear) Cave in Kletno, KZ- tourist route in Gold Mine in Złoty Stok. The map available on the office's website presents the administrative division of Poland into voivodeships and counties on January 1, 2024. Its purpose is to make information available to a wide range of recipients, including: public administration, entrepreneurs, individual users and scientific and research institutions. The authors used it as an illustrative map for scientific and research data

of results reached 70%. At the same time, in all the extraction areas of copper mine 2, it ranged from just above 40% in the main and the western area to just below 70% in the eastern area (Fig. 4). Outside the western area, better fits were obtained when using k_{lmd} correction factors. In the western area, the difference between the estimate obtained by using the k_{1md} factor and that obtained with k_{1mc} was just above 10%. A higher accuracy was obtained for the correction factor k_{1mc} (Fig. 4).

Three-month data

In Kowary, verification of the correction factors was performed using three-month data. Along the tourist route, measurements were conducted at a total of 72 points from November 2000 to 31 January 2005. In the inhalatorium, measurements were conducted at 52 measurement points between August 2001 and 31 January 2005. The mean annual radon concentrations derived from the results of these measurements were 391 Bq/m^3 for the tourist route and 690 Bq/m^3 in the inhalatorium. For successive quarters of the calendar year, mean annual concentrations of radon were estimated using three groups of k_{3m} correction factors recommended for: naturally ventilated facilities (k_{3ma}), facilities with mechanical ventilation systems (k_{3mb}) and all facilities regardless of the ventilation method and the degree of insulation (k_{3mc}).

In the whole facility, the closest to the mean annual value derived from measurements was obtained in the second quarter of the calendar year (from > 70 to 82%) using all the groups of k_{3m} correction factors. The worst fit in the whole facility was obtained in the third and the fourth quarter of the year while using the correction factors recommended for all facilities (k_{3mc}). Differences between the estimated mean annual values and the value obtained from measurements ranged from 80% to nearly 140% (Fig. 5). In the first quarter of the year, higher accuracy of fitting was characteristic of mean annual radon concentrations in the inhalatorium (from 95 to 99%). However, an equally good fit was obtained for the tourist section of the mine (78–82%). In both cases, better results were produced by correction factors k_{3ma} and k_{3mb} respectively (Fig. 5).

To verify quarterly k_{3m} factors, the results of radon concentration measurements conducted at 16 measurement points in the former military facility Osówka from October 2004 to December 2005 were also used. Based on these measurements, the mean annual concentration of radon in the underground complex Osówka was determined to be 200 Bq/m^3. To estimate the mean annual value, three groups of quarterly correction factors: k_{3ma}, k_{3mb} and k_{3mc} were used. As calculations showed, the estimates best fitting the mean annual value derived from measurements are obtained in the second quarter of the calendar year, regardless of the employed k_{3m} correction factor, and in the first quarter of the year for correction factors k_{3ma} and k_{3mb}. In the second quarter of the calendar year, the differences between fits obtained using particular factors are small, reaching less than 10%. In the first quarter of the year, markedly bigger differences between the estimated and the observed mean annual value were obtained using the correction factor k_{3ma}. The observed differences between mean annual values converted using correction factors k_{3mc} and k_{3mb} did not exceed 10% (Fig. 6). In the third quarter of the year, fits comparable to those in the first and the second quarter of the calendar year were obtained using correction factors k_{3mc} and slightly weaker, at the level of c. 60%, using the correction factor k_{3mb}. In the third quarter of the year, estimates based on the correction factor k_{3ma} were almost half as accurate (just under 30/% consistency of results). Also, in the fourth quarter
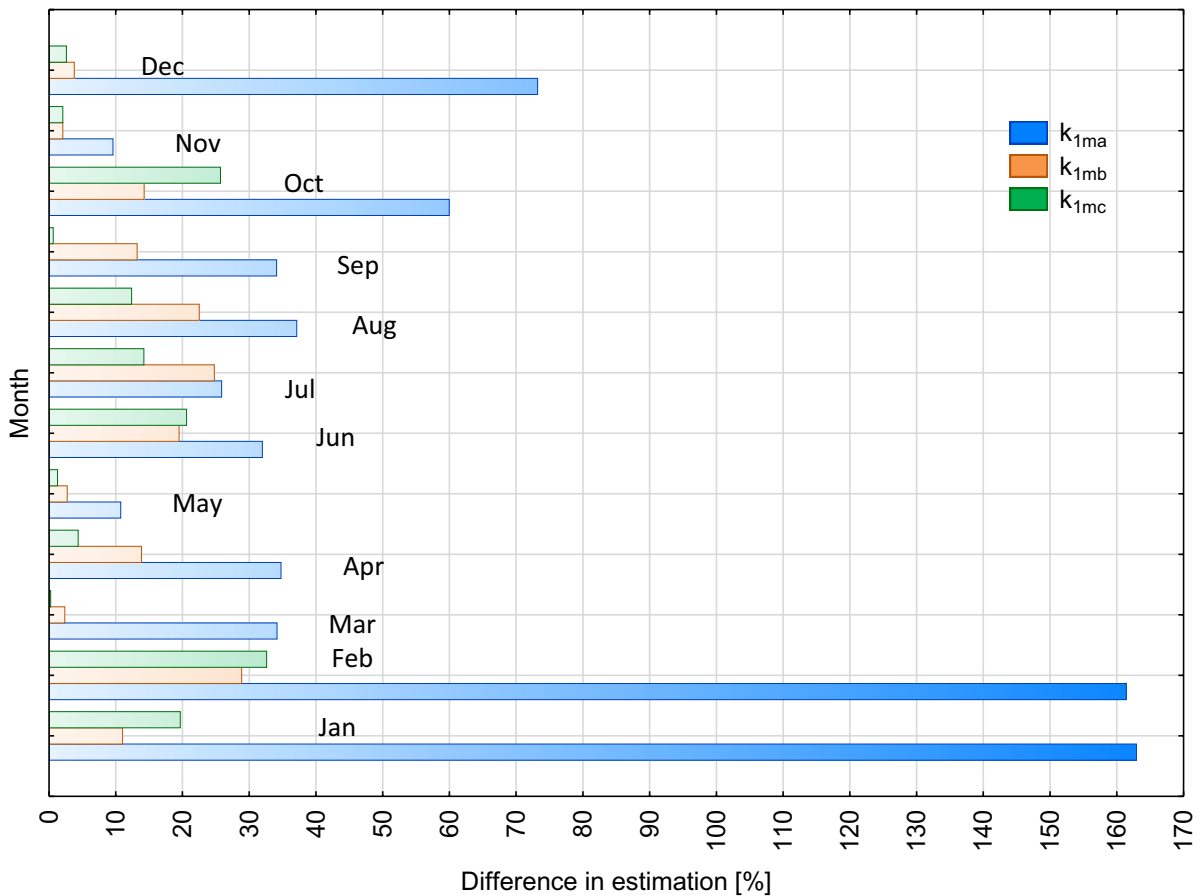
Fig. 2 Differences in fits of mean annual measured value of radon concentration in a tourist facility (cave) to values estimated using correction factors k_{1m}. Explanation: k_{1ma}—monthly correction factor for naturally ventilated facilities well insulated from the atmosphere, k_{1mb}—monthly correction factor for non-insulated facilities, k_{1mc}—averaged monthly correction factor for underground facilities, colours of legend and bars are the same, for bars used a colour blur

of the year, the consistency of the estimated mean annual radon concentration and the value obtained from measurements was lower than in the other three quarters. Mutually comparable fits, at the level of 15–20%, between the estimated and the measured values were obtained for correction factors k_{3ma} and k_{3mb}. The correction factor k_{3mc} was a rather inaccurate conversion factor for estimating mean annual concentration compared to measurement results in the fourth quarter of the calendar year (Fig. 6). The wide variation in result consistency observed in the fourth quarter of the year suggests that it is not the best time to conduct environmental measurements for estimating mean annual values.

Conclusions

The first attempt to verify correction factors against the results of measurements conducted by an accredited dosimetry laboratory in Poland was successful. The mean annual values of radon concentration estimated using groups of monthly and quarterly correction factors recommended for underground facilities are characterized by a high goodness of fit. For a natural space (the cave) the best fit, regardless of the month in which the measurement had been performed, was obtained using correction factors k_{1mb} dedicated to non-insulated spaces (without locks, supporting structures or stoppings), and k_{1mc} dedicated to all underground facilities. In the case of the
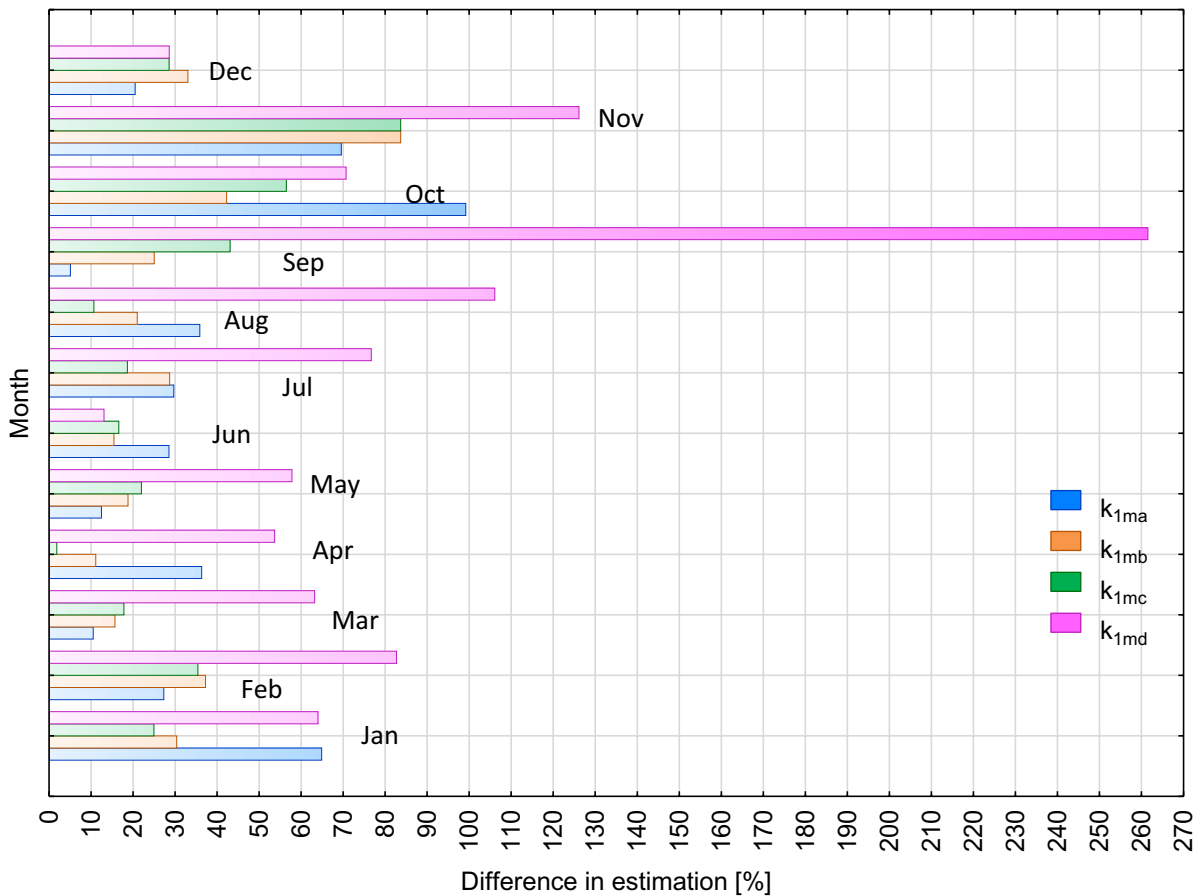
Fig. 3 Differences in fits of mean annual measured value of radon concentration in a tourist facility located in a mine to values estimated using correction factors k_{1m}. Explanation: k_{1ma}—monthly correction factor for naturally ventilated facilities well insulated from the atmosphere, k_{1mb}—monthly correction factor for non-insulated facilities, k_{1mc}—averaged monthly correction factor for underground facilities, k_{1md}—monthly correction factor for facilities with mechanical ventilation system, colours of legend and bars are the same, for bars used a colour blur

correction factor k_{1ma} intended for naturally ventilated spaces with good insulation from the atmosphere, a fit comparable to those obtained with the other two groups of one-month correction factors was obtained for measurements conducted from April to September and in November. On this basis, it was concluded that in order to estimate the mean annual radon level in the warmer part of the year (from May to September), it is better to apply the group of k_{1mc} correction factors. In such cases, the goodness-of-fit of the estimated values to those obtained from measurements is 98% in May, 82% in June, 85% in July, 88% in August, and 99% in September. When it comes to transitional periods, high fitting accuracy, at the level of 95%, was obtained using correction factors k_{1mc} in April, and

k_{1mb}, k_{1mc} and k_{1ma} in November. In the cooler part of the year (from December to March), high compatibility of results was achieved using two groups of correction factors: k_{1mb} and k_{1mc}. The obtained results confirm that the correction factor k_{1ma} should not be used for determining mean annual levels of radon concentration in January and February. Its application for estimating mean annual concentration based on December measurement results enables obtaining a low, 30% fit.

For a tourist facility operating in the workings of a former mine (with a large variation in concentration, reaching even an order of magnitude) a comparable fit between estimated concentrations and values obtained from measurements was obtained using three groups
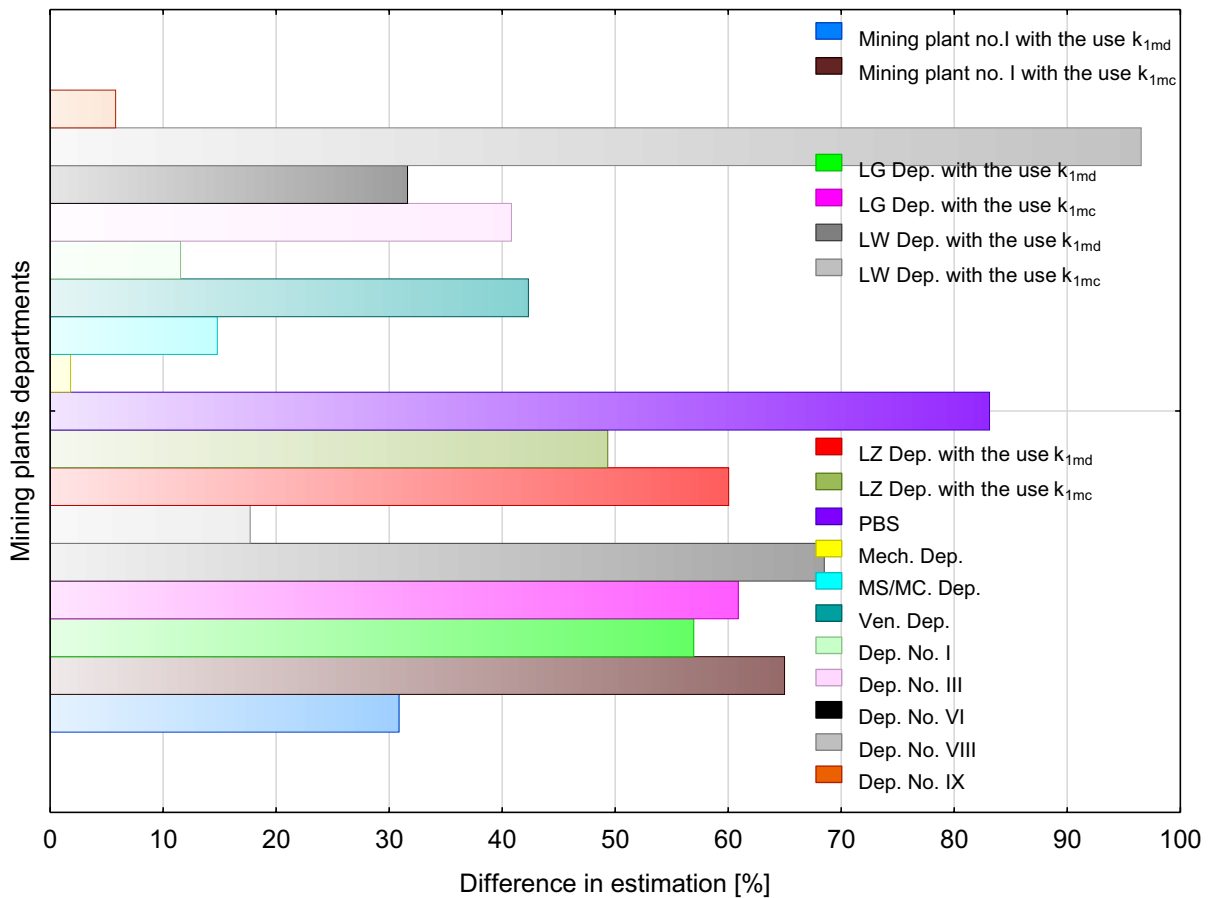
Fig. 4 Differences in fits of mean annual measured value of radon concentration in metal ore mines in Poland to values estimated using monthly correction factors k_{1m} recommended by Fijałkowska-Lichwa and Przylibski (4). Explanation: k_{1mc}—averaged monthly correction factor for underground facilities, k_{1md}—monthly correction factor for mechanically ventilated facilities. Explanation: ZG—mining plant, LG- main area of copper mine No. 2, LZ—western area of copper mine No. 2, LW—eastern area of copper mine No. 2, I, III, VI, VIII, IX—parts of zinc-and-lead mining company, MS/MC—shaft and heavy machinery depot, Mech—mechanical department, PBS—mining and shaft works department, Vent.—ventilation department, $k_{1mc} = 0.38$ in February and 1.60 in December, k_{1md}—1.42 in February, 1.60 in December. In copper mining plants, measurements were conducted in February 2012, and in zinc-and-lead mining plant—in December 2006, colours of legend and bars are the same, for bars used a colour blur

of correction factors, k_{1ma-c}, in March and May, and for all the four groups only in December and June (about 70% fit). In September and November, the best fits were obtained using k_{1ma} correction factors, and in July and August – k_{1mc} correction factors. In the cooler part of the year (December—February) and in the transitional period (April), a better fit was obtained using two groups of correction factors: k_{1mb} and k_{1mc}. Its level exceeded 90% in April and ranged between 90 and 80% in March, May June and August. The lowest accuracy (from 35% to about 2%) was observed for the estimated mean annual value based

on the correction factor k_{1ma} and measurement results obtained in January, October and November.

In active mining plants equipped with mechanical ventilation systems, wide-ranging results of fitting were obtained. In the zinc and lead mining plant, a much worse fit was obtained in extraction departments than in machine depots or rooms for the staff of the ventilation department or mechanical department. In the copper mining company, the best fit of the mean annual value derived from measurement results obtained in February 2012 was obtained using k_{1mc} correction factors in the extraction departments
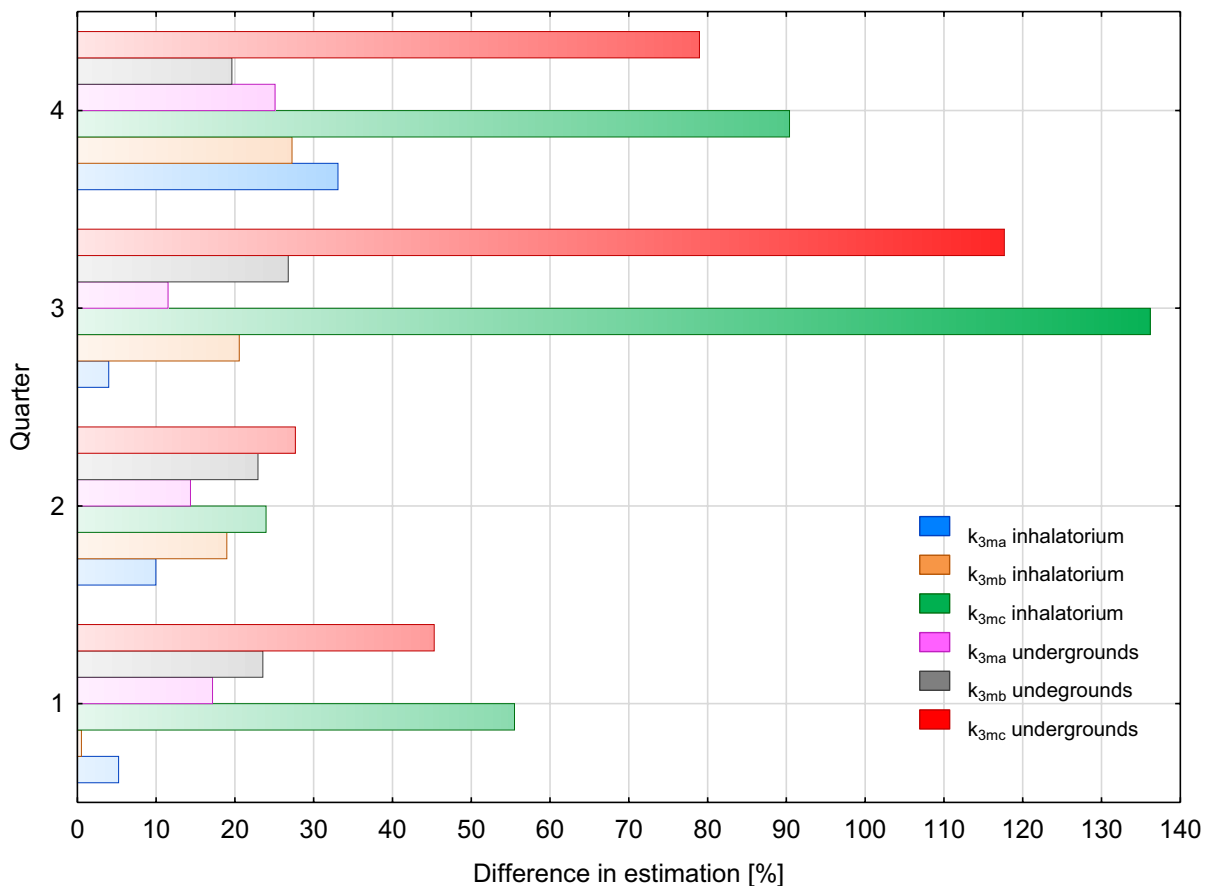
Fig. 5 Differences in fits of mean annual measured values of radon concentration in workings of a former uranium mine in Kowary operating as a tourist route and radon inhalatorium to values estimated using quarterly correction factors k_{3m} recommended by Fijałkowska-Lichwa and Przylibski (4). Explanation: k_{3ma}—quarterly correction factor for naturally ventilated facilities, k_{3mb} quarterly correction factor for facilities with a mechanical ventilation system, k_{3mc}—averaged quarterly correction factor for all underground facilities. Three-month periods corresponded to four quarters of calendar year. Exposure: 1st quarter: from 2160 to 2856 h, 2nd quarter: from 1872 to 2208 h, 3rd quarter: from 2208 to 2616 h, 4th quarter: from 2208 to 2592 h, colours of legend and bars are the same, for bars used a colour blur

of mine No. 1 and in the main area of mine No, 2. In the extraction departments in the western and eastern area of mine 2, the best fit was obtained using k_{1md} correction factors. The obtained results confirm that mean annual concentrations in the extraction areas of copper mining plants can be estimated using k_{1mc} and k_{1md} correction factors. In zinc and lead mining plants, on the other hand, these groups of k_{1m} correction factors provide a far better fit to measurement results obtained in departments remote from the extraction areas. Such variation in the obtained results was most likely due to the air circulation conditions. The mean level of concentration was determined on the basis of the results of environmental dosimetry measurements conducted both at workplace exposure (during effectively worked time) and during preparatory time spent in the bathroom, the lamp room, the changing room, or on the way to the workplace.

In active metal ore mines, large variations in the fit between estimated values and measurement results was observed. In copper mines, it ranged 28%-83%, and in the zinc and lead mining plant—from 58 to 98%. Therefore, the recommended choice of the optimal period of the year for conducting measurements and estimating the mean annual value in active mines ought to be verified. Such verification should be based on measurements conducted for at least a few months, and preferably one calendar year.
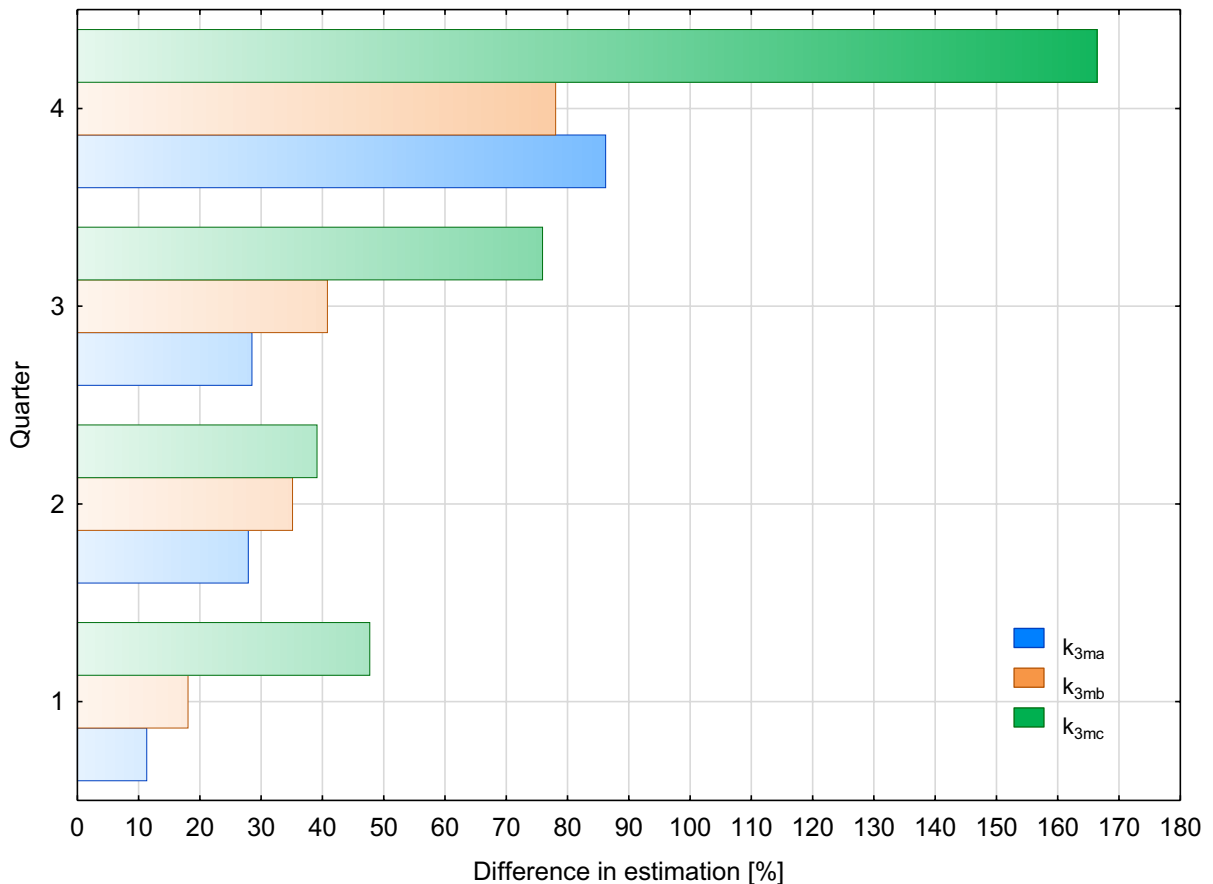
Fig. 6 Differences in fits of mean annual measured values of radon concentration in former military facility Osówka operating as a tourist route to values estimated using quarterly correction factors k_{3m} recommended by Fijałkowska-Lichwa and Przylibski (4). Explanation: k_{3ma}—quarterly correction factor for naturally ventilated facilities, k_{3mb}—quarterly correction factor for facilities with a mechanical ventilation system, k_{3mc}—averaged quarterly correction factor for all underground facilities. Three-month periods corresponded to four quarters of the calendar year. Exposure: 1st quarter: 2160 h, 2nd quarter: 2828 h, 3rd quarter: 2880 h, 4th quarter: 2208, colours of legend and bars are the same, for bars used a colour blur

Along the tourist routes and in the inhalatorium, both in the former uranium mine and in the former military facility, the best fit of estimated values to those from measurements was obtained using three groups of quarterly correction factors in the second quarter of the calendar year. The biggest differences in the fit of mean annual values were observed in the third and the fourth quarter of the year for correction factors k_{3mc} recommended as averages for all underground facilities. In the first quarter of the year, a much better fit (differing by 15% to 30% from the estimated annual mean of radon concentration) was obtained using k_{3ma} and k_{3mb} factors. Hence, it was concluded that in order to determine mean annual values of radon concentration in tourist facilities located in former mines, it is best to use correction factors k_{3ma} and k_{3mb} in the first, the third and the fourth quarter of the calendar year. Additionally, when determining a mean annual concentration along a tourist route and in an inhalatorium located in a former mine, or in a military facility, one should not use correction factors k_{3mc} in the third and the fourth quarter of the calendar year. Their application is possible in the first quarter of the year, but the obtained results may differ by 45% to 55% from the real values obtained from measurements. This fit is a half to almost a fifth of that obtained when using k_{3ma} and k_{3mb} factors.

The results of the authors' research have made it possible to indicate the optimal period (the month

and quarter of the year) for conducting environmental measurements aimed at determining the mean annual value of radon concentration (Table 2). The highest accuracy of one-month estimation can be obtained while conducting environmental measurements of radon concentration in underground facilities in March, April, May and September. In three-month (quarter) periods, these are the first and the second quarter of the calendar year (Table 2). Additionally, in a natural space (a cave), it is best to estimate the mean annual value of radon concentration using two groups of correction factors: k_{1mc} and k_{1mb}. When determining the mean annual value along a tourist route located in the workings of a former mine with a markedly varied level of radon concentration, it is best to use the k_{1ma} factor, recommended for naturally ventilated spaces well insulated from the atmosphere, in March and September. In April, these should be k_{1mb} and k_{1mc} correction factors. Along tourist routes and in inhalatoriums operating in the workings of former mines and in military facilities, the best period for conducting radon concentration measurements is the second quarter of the calendar year (from April to June). Due to a significantly varied range of fits between the obtained results (from 15% to more than 75% for k_{3ma} and from just above 20% to 80%

Table 2 Authors' recommendations for values of correction factors k_{1m} and k_{3m} in underground facilities relative to optimal periods for conducting environmental measurements

Type of object	Recommended exposure period	Recommended correction factors	Match compliance [%]
Cave	III	k_{1mb}: 1.30 or k_{1mc}:1.16	98% or 99% respectively
	IV	k_{1mc}: 0.88	95%
	V	k_{1mc}: 0.74	98%
	IX	k_{1mc}: 0.95	99%
	XI	k_{1mb}: 1.30, k_{1mc}: 1.30, k_{1ma}:1.20	98%, 98%, 90% respectively
	XII	k_{1mb}: 1.50 or k_{1mc}:1.60	95% or 97% respectively
Tourist route in mine	III	k_{1ma}:1.56	90%
	IV	k_{1mc}: 0.96 or k_{1mb}: 0.88	98% or 90% respectively
	IX	k_{1ma}: 0.63	95%
Mining company	In colder period: XII	k_{1mc} or k_{1md} 1.60	For mining area (range): 58–98%
Tourist route in abandoned uranium mine	Quarter no. 1 (January-March)	k_{3ma}: 0.62	82%
	Quarter no. 2 (April-June)	k_{3ma}: 0.76	82%
	Quarter no. 3 (July–September)	k_{3ma}: 2.14	88%
	Quarter no. 4 (October-December)	k_{3mb}: 1.31	80%
Inhalatorium in abandoned uranium mine	Quarter no. 1 (January-March)	k_{3mb}:1.40, k_{3ma}: 0.62	99%, 95% respectively
	Quarter no. 2 (April–June)	k_{3ma}: 0.76	90%
	Quarter no. 3 (July–September)	k_{3ma}: 2.14	95%
	Quarter no. 4 (October–December)	k_{3mb}: 1.31	72%
Tourist route in military object	Quarter no. 1 (January–March)	k_{3ma}: 0.62, k_{3mb}: 1.40	89%, 82% respectively
	Quarter no. 2 (April-June)	k_{3ma}: 0.76	72%
	Quarter no. 3 (July–September)	k_{3ma}: 2.14	72%
	Quarter no. 4 without recommendation	k_{3m}	Too high difference of estimation

Explanation: ZG—mining plant, k_{1m} – monthly correction factor, k_{3m} – quarterly correction factor, k_{3ma} – quarterly correction factor for naturally ventilated facilities, k_{3mb} – quarterly correction factor for facilities with mechanical ventilation systems, k_{3mc} – averaged quarterly correction factor for all underground facilities, k_{1ma} – monthly correction factor for naturally ventilated facilities well insulated from the atmosphere, k_{1mb} – monthly correction factor for non-insulated facilities, k_{1mc} – averaged monthly correction factor for underground facilities, k_{1md} – monthly correction factor for facilities with mechanical ventilation systems

for k_{3mb}), the fourth quarter of the year should not be chosen for estimating the mean annual value of radon concentration. The obtained values might be less accurate compared to those obtained from measurements. This has also been confirmed by the results of research by Fijałkowska-Lichwa and Przylibski (2022).

The results of the assessment based on archival data (years 1995–2012) provided by the Institute of Occupational Medicine in Łódź have confirmed that monthly and quarterly correction factors are a very well-suited tool for estimating mean annual radon concentrations in the warmer part of the year. This is particularly important in terms of radiation protection, as this the time when the highest risk of exposure to radon and its progeny occurs. The correction factors recommended by the authors may be successfully used to determine mean annual radon concentrations in underground facilities in other countries in Europe and worldwide located in similar climatic zones as Poland. The authors' findings correspond to those obtained by Fijałkowska-Lichwa and Przylibski (2022).

Author contributions Lidia Fijałkowska-Lichwa is the initiator and the author of the first version of the manuscript. Lidia Fijałkowska-Lichwa prepared the data for analyses. She processed them statistically and interpreted the results. Jerzy Olszewski prepared the results of radon concentration measurements. Both authors interpreted the obtained results. Both authors have read and approved the final manuscript.

Data availability All relevant data and materials are presented in the paper.

Declarations

Conflict of interest The authors state that there are no conflicts of interest regarding the publication of this article and that there are no financial ties to disclose. The authors declare no competing interests.

Ethical approval The results of the 1995–2012 radon concentration measurements used to verify the correction factors are the property of the IMP in Łódź. The heads of the entities which had conducted the measurements did not object to their results being used in scientific publications. The results of radon measurements had been partially published in scientific publications of the IMP in Łódź. The database of the correction factors used in the paper has been published in its entirety.

Informed consent Consent for publication has been obtained.

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