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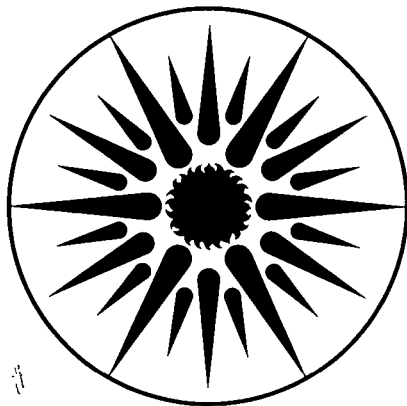
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March 1994

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Assessment of Lung Deposition and Breathing Rate
of Underground Miners in Tadjikistan

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Abstract

Deposited gamma-ray activity in miners' lungs and airborne concentrations of ^{222}Rn decay products were measured in a metal mine in Tadjikistan. Measurements for about 100 miners were performed, using filtered air samples to estimate their decay-product exposures and a field gamma-ray system to determine corresponding chest activities. These two quantities yielded the deposited lung activity per unit exposure, which is proportional to the product of the average minute volume and the fractional lung deposition, called here the "filtration ability of lungs" (FAL). The group-average FALs were found to be, for drillers, assistant drillers, and inspection personnel, respectively, 0.0079, 0.0067, and 0.0052 m^3 min^{-1}, with approximately 20% standard error. Independent measurements were also made, for a group of mine workers engaged in light work, not only of FAL, but also of breathing rate (minute volume), permitting estimation of the lung deposition fraction, found to average 0.34 ± 0.03. Finally, this value was used together with the group FALs noted to yield upper-bound estimates of the average minute volumes for these job categories, respectively, 0.023 ± 0.004, 0.020 ± 0.004, and 0.015 ± 0.003 m^3 min^{-1}.

KEY WORDS: RADON, BREATHING RATE, MINES, LUNG DEPOSITION, DOSE

INTRODUCTION

Lung deposition fractions and breathing rates, or more specifically minute volumes, are important quantities in the dosimetry of ^{222}Rn decay products, but there have been few measurements of these quantities in the occupational setting. Some results have been reported for the total decay-product deposition fraction in the lungs by measuring the difference in concentration in inhaled and exhaled air in laboratory chambers and in mines [1,2,3]. Breathing rates, particularly in underground mines, cannot usually be determined accurately because the usual measurement techniques are cumbersome and disturb normal conditions. We here report new measurements, using an alternative approach, yielding deposited activity per unit exposure and minute volumes for miners working underground in a lead, zinc, and bismuth mine in Tadjikistan in the late 1960s.

When the short-lived decay products of ^{222}Rn - ^{218}Po, ^{214}Pb, and ^{214}Bi (^{214}Po) - are inhaled, a small fraction, e.g., 0.02-0.05, deposits on the bronchial airways, while a larger fraction, up to half, deposits in the lower lung or pulmonary region. Still, the dose from the alpha emitters ^{218}Po and ^{214}Po deposited in the bronchial region is responsible for the observed increase in lung carcinoma among miners following ^{222}Rn exposure [4,5,6], presumably because of differing geometries causing a higher proportion of the alpha energy to be deposited in the epithelial cells at risk in the bronchi or because of greater sensitivity there. The dose from the beta and gamma emitters ^{214}Pb and ^{214}Bi, by comparison, is relatively insignificant because a smaller fraction of emitted energy is deposited in the relevant cells, and because it has a lower biological effectiveness.

Nonetheless, the gamma radiation from these radionuclides provides a means of monitoring deposited decay-product activity. The study reported here takes advantage of high

airborne concentrations occurring previously in mines, and the large pulmonary deposition fraction, to directly measure ^{214}Pb and ^{214}Bi activity deposited in the lungs of approximately 100 miners in three job categories, and to calculate deposited activity per unit exposure, proportional to the product of breathing rate (minute volume) and deposition fraction. Deposited gamma activity was measured using a portable gamma scintillation detector against which miners could press their chests, usually in the mine near the site of mining operations. Together with measurements of breathing rate and deposited activity in a small group of miners engaged in light activity, yielding an estimate of deposition fraction, these data permit estimation of upper-bound average breathing rates for miners engaged in three different levels of activity.

A DIRECT METHOD FOR DETERMINING DEPOSITED ACTIVITY IN THE LUNG

Substantial work has been devoted to estimating deposited decay-product activity, and resulting dose to the cells in the bronchial airways, based on airborne decay-product concentrations and presumed lung physiology [7,8,9,10,11,12,13,14,15]. Of more interest for present purposes are equations derived by Ruzer[16,17] that relate deposited activity directly to airborne concentrations and that also provide a basis for estimating dose. Gamma-ray activity in the lung (in Bq m^{-3}) from decay-product deposition can be described in a general mathematical form as,

$$A_\gamma = vk\{[\varPhi_b{}^a (\theta, t) + \varPhi_c{}^a (\theta, t)]q_a \\ + [\varPhi_b{}^b (\theta, t) + \varPhi_c{}^b(\theta, t)]q_b + \varPhi_c{}^c (\theta, t)q_c\}, \tag{1}$$

where

q_a, q_b and q_c = airborne concentration of ^{218}Po, ^{214}Pb, ^{214}Bi , respectively, in

Bq m^{-3} (with the very short-lived ^{214}Po having the same concentration as ^{214}Bi);

Φ_j^i (θ, t), etc. = exponential functions for the contribution of airborne radioactive species i

to lung activity j that depend on the exposure duration, θ, the time, t ,

following exposure, and the radionuclide decay constants;

v = breathing rate (minute volume) in m^3 min^{-1} ; and

k = average fractional deposition in the lung, presumed to be the same for

each decay product.

Only a small fraction of the lung gamma activity is from bronchial deposition, so that this may be

taken to represent primarily pulmonary gamma activity.

The gamma activity in Eq. (1) can be given in a simplified form after attaining steady state,

assuming an average breathing rate and deposition fraction,

$$A_\gamma = (v\ k)\ [8.8\ q_a + 77.3\ q_b + 28.4\ q_c]\ Bq. \tag{2}$$

The data available from this study are the lung gamma-ray activity, A_γ, and the total

^{214}Pb plus ^{214}Bi activity concentration in air. Over a wide range of physical decay-product

equilibria, the ratio of these measurements can be reduced to

$$A_\gamma\ /(q_b + q_c) = 60\ (vk)\ m^3. \tag{3}$$

This simplification is analogous to that associated with simple fast decay-product monitoring

techniques.

The lung gamma-activity measurements were used historically as a control over the

permissible pulmonary dose for miners in several types of underground mines in Tadjikistan[18].

Equations (2) and (3) for the gamma-activity in the lung led to the idea of using gamma-activity

measurements as a source of information on the breathing characteristics of the working

personnel.

Although arising primarily from pulmonary gamma measurements, this information may in turn yield information on the variability in bronchial deposition. The fractional aerosol deposition in the bronchial tree has been measured in hollow casts of the human airways[19] and was shown to vary approximately with the inverse square root of flow rate, $Q^{-1/2}$, over a wide range of particle size. Total deposition (and thus alpha dose) in an airway, proportional to flow rate times the deposition fraction, may therefore be given as:

$$\text{Total airway deposition} \approx Q\,Q^{-1/2} \approx Q^{1/2}. \tag{4}$$

Thus, the alpha dose in the airways is related crudely to $v^{1/2}$. The variability of the bronchial dose due to breathing-rate differences can then be assessed if the latter are known.

MEASUREMENT TECHNIQUE

The measurements reported here were carried out in a non-uranium mine in Tadjikistan (former U.S.S.R.) with a special instrument having two probes (shown in Fig. 1).[20] The measurement of the concentration of ^{222}Rn decay products in the breathing zone was performed by alpha counting of 1.8 or 3.6 cm diameter filtered air samples with a ZnS scintillation probe, using a two-count analytical procedure.

The measurement of gamma-ray activity deposited in the lung was performed using a low background gamma probe consisting of a collimated 80 x 40 mm NaI(Tl) crystal in 50 mm of lead shielding. The background counting rate was determined by measuring each miner before entering the work area. Miners pressed their chests to the window of the NaI(Tl) detector after removing their outer clothing and the gamma-count rate was measured. A similar measurement was taken after leaving the work place, and deposited activity in the lung was calculated from the net count rate.

For calibration, a chest phantom was used. The phantom consisted of a simulated torso filled with rice and with point calibration sources placed in various positions to replicate inhaled activity deposited in the pulmonary region. The sources were standardized by the Mendeleev Metrological Institute in St. Petersburg. The combined efficiency for ^{214}Pb and ^{214}Bi was found to be 0.006 counts per decay.

For this type of measurement constancy of the gamma-ray background is important. The measurements showed that the background for the same person did not vary by more than 3% with repeated counts over many days. Background did vary for persons with different body thickness, being higher for thinner chests (Figure 2).

In most cases, the gamma-monitor was placed underground near the workplace. In some cases, workers needed 30-40 minutes to reach the detector. In this case, a correction for decay of ^{222}Rn decay products in the lung was introduced, as discussed below in the next section. Figure 3 shows the decay of ^{222}Rn daughters in the lungs of three miners. The vertical axis is the logarithm of activity in arbitrary units. These data, with an effective half life of approximately 40 min, showed that no substantial clearance of radon progeny from the pulmonary region occurred. However, in the use of this instrument, other corrections have been made, e.g., due to different ratios between ^{214}Pb and ^{214}Bi in the lung and in the calibration source. [18]

The detection limit was adequate in that when the decay-product concentration in air was 1.2 kBq m^{-3}, the gamma activity in the lung after more than 1 hour of exposure was approximately 370 Bq. The gamma-ray scintillation counter background in the mine for an individual averaged 30 cps and the measurements were usually made for 100 seconds. The efficiency of 0.006 then implies a lower limit of detection of 400 Bq, i.e., the activity in the lung that could be detected as above background 95% of the time. [21]

(The direct measurement of the activity in the lungs of miners was also used for on-site evaluation of the pulmonary alpha dose for individuals and groups of miners in uranium mines in the north of Kazashtan, Uzbekistan and in non-uranium mines in the north and south of Tadjikistan, totalling about 800 measurements. Dosimetric and epidemiologic studies were performed on 2500 miners in 72 metal mines. In some of these mines, the direct measurement of the gamma-ray activity in the lungs was used in assessing the effectiveness of respirators. According to the technical specifications, the respirators should have been 99.9% efficient. However, the measurements showed that the actual efficiency varied from 67 to 95% depending upon the individual's training and the type of work[22]. It should be pointed out that it is very difficult to use respirators while doing heavy work.)

THE FILTRATION ABILITY OF THE LUNGS (FAL)

With the high ^{222}Rn decay product concentrations observed in these mines, both the time-average activity in the lung and the air concentrations could be measured accurately. Based on Eqs. 1-3, these results yield values for the product v k, called the filtration ability of the lungs (FAL)[22], e.g., FAL $= A_{\gamma}/[60(q_b + q_c)]$ m^{3}min^{-1} (from Eq. 3). We may generalize this to take account of the exposure period and time since exposure as:

$$(FAL) = v\,k = A_{\gamma}\,[F(\theta, t)]/(60\,q)\ \text{m}^3\text{min}^{-1}$$

where $q = q_b + q_c$

$F(\theta,t)$ = theoretical function accounting for duration of exposure θ and decay in the lung after time, t, if the measurement is not immediate.

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$F(\theta,t)$ is given approximately by the expression $\lambda_{eff}/(1-e^{-\lambda_{eff}\theta})$, $\lambda_{eff}=\ln2/T \approx \ln2/40$ min, where T is the observed effective half life for decay in the lung (from Fig.3).

Measurements were performed for three groups - drillers, auxilliary drillers and inspection personnel - totalling approximately 100 workers, without disturbing the working conditions. The average, standard error, and median values for a total of 297 air samples and 391 lung measurements are shown in Table 1 (extracted from References 22-24). From the average and median values, the air concentrations and the chest gamma-ray activity are estimated to be distributed lognormally with a geometric standard deviation (GSD) of 2.0 to 2.5.

From air concentrations and lung activities measured on the same day for individual miners, individual FALs were calculated. The average FALs calculated for the three groups - drillers, auxiliary drillers, and inspection personnel - are 0.0079, 0.0067, and 0.0052 m^3 min^{-1}, respectively (with standard errors on each of approximately 20%). Thus the filtration ability of the lung varies only moderately among these groups, consistent with the observations mentioned below indicating that, even for drillers, most time is spent at light to moderate work. Note also that the average and median FALs are similar for each group, suggesting a normal rather than a lognormal distribution.

The study also included a comparison of the putative absorbed dose in lung as indicated by the direct monitoring of lung activity and associated airborne activity and by inference using standard lung values. The indirect calculation was based on standard values for the breathing rate, 0.020 m^3 min^{-1}, and deposition coefficient, 0.25, in use at the time. The average and median ratios of FAL for the measured and calculated values are shown in the last column of Table 1.

The average ratio is substantially greater than 1, indicating the tendency for the actual FAL (and hence dose) to exceed the standard value based on assumed breathing rates and

deposition fractions. The calculation of FAL using standard values for the minute volume showed that in 76% of the measurements (from 168 man-shifts), individual activities of decay products in the lungs of miners could be higher than predicted from assumed average values of breathing rate and pulmonary deposition, by up to a factor of 8. There was no direct correlation between average concentration in the air and calculated activity in the lung. The reason for this difference was clearly that the actual breathing rate and deposition coefficients are substantially different from the standard values used in the calculation.

The Filtration Ability of the Lungs (FAL) is a characteristic of each individual, and group averages maybe taken to be typical for the type of work considered. The FAL is a result of various factors such as physical effort (the nature of the job activity), physical characteristics such as lung morphometry, aerosol particle size distribution, etc..

ASSESSMENT OF THE BREATHING RATE OF MINERS

The minute volume of working miners may be estimated from a measurement of FAL=vk if we have an independent measurement of the deposition fraction, k. There are three reports of such measurements, in each case by measuring the decay products in inhaled and in exhaled air. In the earliest, Harley and Fresco[1] measured deposition of ^{222}Rn decay products in 2 people in a laboratory chamber, reporting an average deposition in the total lung of 45%.

George and Breslin[2] later measured ^{222}Rn decay-product deposition in 3 people in the Beaverlodge mine in Saskatchewan, Canada, the Schwartzwalder mine in Colorado, and in laboratory air. They reported that deposition ranged from 25-40% for tidal volumes ranging from 0.008 to 0.0012 m^3 and that there was no change with breathing frequency. The deposition was

42, 33, 32% for ^{218}Po ^{214}Pb and ^{214}Bi at Beaverlodge and 33% for total activity measurements in the Schwartzwalder mine.

Holleman[3] also measured deposition of radon decay products in lungs of miners by measuring ^{222}Rn decay-product concentration in the inhaled and exhaled air. According to their measurements, the deposition was in the range of 0.30-0.65 and depended on the breathing frequency and tidal volume. They reported that the tidal volume was the most important determinant of deposition. According to their study, for a breathing frequency of 18 breaths per minute and a tidal volume 0.0012 m^3, the deposition fraction for each of the decay products was 0.504, 0.447 and 0.406.

Available techniques for measurement of breathing rate change the actual breathing conditions in most cases, especially for hard-working personnel. Furthermore, measurements of the deposition coefficient, based on the difference between concentrations in inhaled and exhaled air, are probably not as reliable as a direct measurement of lung deposition. For this reason, the measurement of FAL in different groups of workers may yield the best assessment of breathing rate when deposition is known and vice-versa.

In the Tadjikistan mine, the breathing rate for 14 inspection personnel doing light work was measured. Measurements could be made using the conventional minute volume measurement technique with Douglas air bags and a gas meter. This did not disturb their normal working conditions markedly[23,24]. Breathing rate was measured approximately every hour during 2-3 shifts, and the average for each shift was calculated from 3-8 measurements. The FAL was calculated for each individual using Eq.(5) from the average of 10-12 measurements of ^{222}Rn decay products during a shift and from the average of a series of 10-12 gamma-ray activity measurements, made throughout and at the end of a shift. The results of these measurements and

the calculated deposition coefficient are presented in Table 2 for 14 technical inspection personnel. The average fractional pulmonary deposition for this group was 0.34 ± 0.03.

We argue that the average deposition coefficient for workers other than inspection personnel (especially drilling miners) should not be less than 0.34, since total lung deposition should increase with level of physical activity, as discussed earlier. Using a value of 0.34 for the lung deposition, nominal breathing rates for drillers, auxilliary drillers and supervisory personnel were calculated based on the group-average FALs given in Table 1. These values are shown in Table 3, indicating for the group with the highest level of activity (drillers) an average breathing rate of $0.023 \text{ m}^3 \text{ min}^{-1}$. This average minute volume should be taken as an upper bound, as the lung deposition fraction during drilling may be somewhat higher than the value of 0.34 for inspection personnel used in the calculation.

The correct assessment of the average breathing rate for an 8-hour work shift must take into account the time distribution of different types of work (especially heavy work, such as drilling) during the shift. Observation of the time distribution for 6 miners with the job category of driller and drilling supervisor (bore master) in this metal mine was conducted.[23] The results of these observations are presented in Table 4. According to this study, the average time distribution for the shift was: resting 13%; easy work 39%; medium work 40%; hard work 8%. These data show that even if the breathing rate is high for a short period of time, the average breathing rate for the shift is similar to that for medium to light work. Taking into account the time distribution of work type, the average breathing rates for each shift were calculated, using nominal values from other work, and these are shown in Table 4.

DISCUSSION

Based on measurements of airborne concentrations and associated gamma activity in the lung, one is able to calculate the "filtration ability of the lung" (FAL) for individual miners, essentially a measure of the volumetric rate at which the individual removes ^{222}Rn decay products present in the surrounding atmosphere. In the measurements reported here, this rate if found to vary on average from 0.0052 to 0.0079 m^3 min^{-1} from inspection personnel to drillers. This is only a modest dependence on type of mine work, but is consistent with the observation that, even for drillers, the average proportion of time spent in heavy activity can be small, about 8% in this case. (To what extent this can be generalized to other mines remains to be seen.) On the other hand, as indicated in Table 1, and more explicitly in Table 2, individual variations in FAL can be quite substantial.

The small associated set of measurements of both FAL and minute volume for 14 inspection workers permitted inference of the average deposition fraction, 0.34 ± 0.03, with a standard deviation of 0.11, for this group. This result is consistent with values arising from other studies, noted above, especially considering that these workers were engaged in light activity.

Taking this deposition fraction as a minimum value for the three job categories for which average FALs were determined independently, we may calculate upper-bound average minute volumes for these three groups, ranging from 0.015 to 0.023 m^3 min^{-1} . Note that these are values for average shift work, and again indicate relatively small differences from light-activity to heavy-activity categories. (Furthermore, the data of Table 2 indicate relatively small individual variation in breathing rates - with a relative standard deviation of 13% - compared with larger differences in FAL (and hence dose) - with a relative standard deviation of 45%.)

Minute volumes for miners have often been presumed to be larger than found in this work. For example, an evaluation of the relative dose from radon decay products in mines and homes[15] used a minute volume for miners of 0.031 m^3min^{-1}, approximately 50% larger than the rate found here. On the other hand, these lower rates for miners may have only a moderate effect on comparative dosemetry, since there is evidence that minute volumes for members of the public at home and elsewhere have also been overestimated.[26]

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Figure Captions

Figure 1. Instrument for measuring Filtration Ability of Lungs. The instrument at the right contains a pump for drawing air through a filter contained in a probe held in a miner's breathing zone. The filter (1) is then placed in the sample holder and the collected alpha-activity is measured by a detector inside the instrument. Gamma activity in a miner's lungs is measured using a NaI crystal (2), using a phototube whose power is provided and pulses counted by the instrument. Also shown is a 50 mm lead shield (3) and a set of collimators (4) for the NaI detector.

Figure 2. Gamma background versus chest thickness. The data shown are selected from direct gamma measurements in a large number of miners.[22-23]

Figure 3. Decay of gamma activity in lungs of miners. The gamma activity was monitored as a function of time for three miners.

Table 1. Measured Air Concentration of ^{214}Pb and ^{214}Bi, Gamma-ray Activity in Miners' Lungs and Calculated Filtration Ability of Lungs (FAL) for Different Groups of Miners in a Metal Mine in Tadjikistan.

Job Category	Number of air samples	Concentration of ^{214}Pb+^{214}Bi (kBq m^{-3})			Activity in Lungs (kBq)[a]				FAL = vk (m^3 min^{-1})			FAL$_{meas}$/ (FAL)$_{std}$[b]	
		Average	Std. Error	Median	No. of Lung Measurements	Average	Std. Error	Median	Average	Std. Error	Median	Average	Median
Drilling	92	5.92	0.55	3.7	219	2.66	0.22	2.59	0.0079	0.0014	0.0090	1.6	1.8
Auxiliary	76	6.88	0.81	5.2	104	2.63	0.30	1.92	0.0067	0.0015	0.0062	1.3	1.25
Inspection Personnel	129	11.1	1.11	7.4	68	3.26	0.33	2.11	0.0052	0.0011	0.0055	1.4	1.1
Average		8.9	0.9	5.2		2.85	0.26	2.22	0.0066	0.0011	0.0069	1.4	1.4

[a] Actual gamma activities at time of measurement. In calculating FAL a correction was made on A_γ to account for decay between end of shift and time of measurement, in all cases less than 1 hr.

[b] FAL$_{meas}$ is the value based on measured data, FAL$_{std}$ is the calculated value based on assumed standard breathing rate of 0.020 m^{3}min^{-1} and standard fractional lung deposition of 0.25.

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Table 2. Measured Minute Volume, FAL and Calculated Lung Deposition fraction of Technical Inspection Personnel in an Underground Metal Mine in Tadjikistan.

Individual's Job Category	Date	FAL = vk ($m^3 min^{-1}$)	Minute Volume, v ($m^3 min^{-1}$)	Pulmonary Deposition Coefficient, k
Dosimetrist A	7/27/68	0.003	0.012	0.25
Dosimetrist A	9/12/68	0.0028	0.012	0.23
Dosimetrist A	9/15/68	0.0029	0.012	0.25
Dosimetrist B	7/27/68	0.0039	0.013	0.30
Dosimetrist B	9/12/68	0.0022	0.011	0.2
Dosimetrist C	7/27/68	0.0072	0.015	0.48
Dosimetrist C	9/12/68	0.0068	0.014	0.5
Dosimetrist C	9/18/68	0.008	0.014	0.57
Signalist A	7/27/68	0.0021	0.010	0.21
Signalist A	9/18/68	0.0037	0.012	0.32
Signalist B	9/12/68	0.0041	0.011	0.37
Signalist B	9/15/68	0.0034	0.010	0.34
Sample Man	9/12/68	0.0041	0.014	0.3
Sample Man	9/15/68	0.0056	0.014	0.4
	Average	0.0042±0.0005	0.0123±0.0004	0.34±0.03
	Median	0.0038	0.012	0.31
	Minimum	0.0021	0.010	0.20
	Maximum	0.0080	0.015	0.57

Table 3. Upper-Bound Estimates of Average Minute Volume for Three Different Job Categories in an Underground Metal Mine in Tadjikistan.

| Group of Workers	Upper-Bound Estimated Group-Average Minute Volume (m^3 min^{-1})	
	Arithmetic Mean ± standard error	Median
Drilling	0.023±0.004	0.0264
Auxiliary	0.019±0.004	0.018
Inspection Personnel	0.015±0.003	0.016

Table 4. Time Distribution of the Work Status of Miners in an Underground Metal Mine in Tadjikistan.

Job Category	Number of Shifts	Duration in specified work status (min.)[a]				
		Resting	Easy	Medium	Hard	Average Nominal Breathing Rate for the Shift (m^3 min-1)[b]
Shaft Sinker A	2	86	180	86	3	0.019
Shaft Sinker B	2	14	100	217	29	0.022
Shaft Sinker C	1	34	116	163	47	0.0224
Shaft Sinker D)	1	25	180	94	61	0.0236
	Average±SD	45±16	142±29	144±40	35 11	0.0213±0.0044
Bore Master-Supervisor A	1	220	46	90	4	0.0168
Bore Master-Supervisor B	1	162	18	148	32	0.0195

[a] Total Observation Time 480 min.

[b] Average calculated assuming standard breathing rates, ranging from 10 m^3min-1 for resting to approximately 40 m^3min-1 for hard work, based on results from a coal mine.[25]
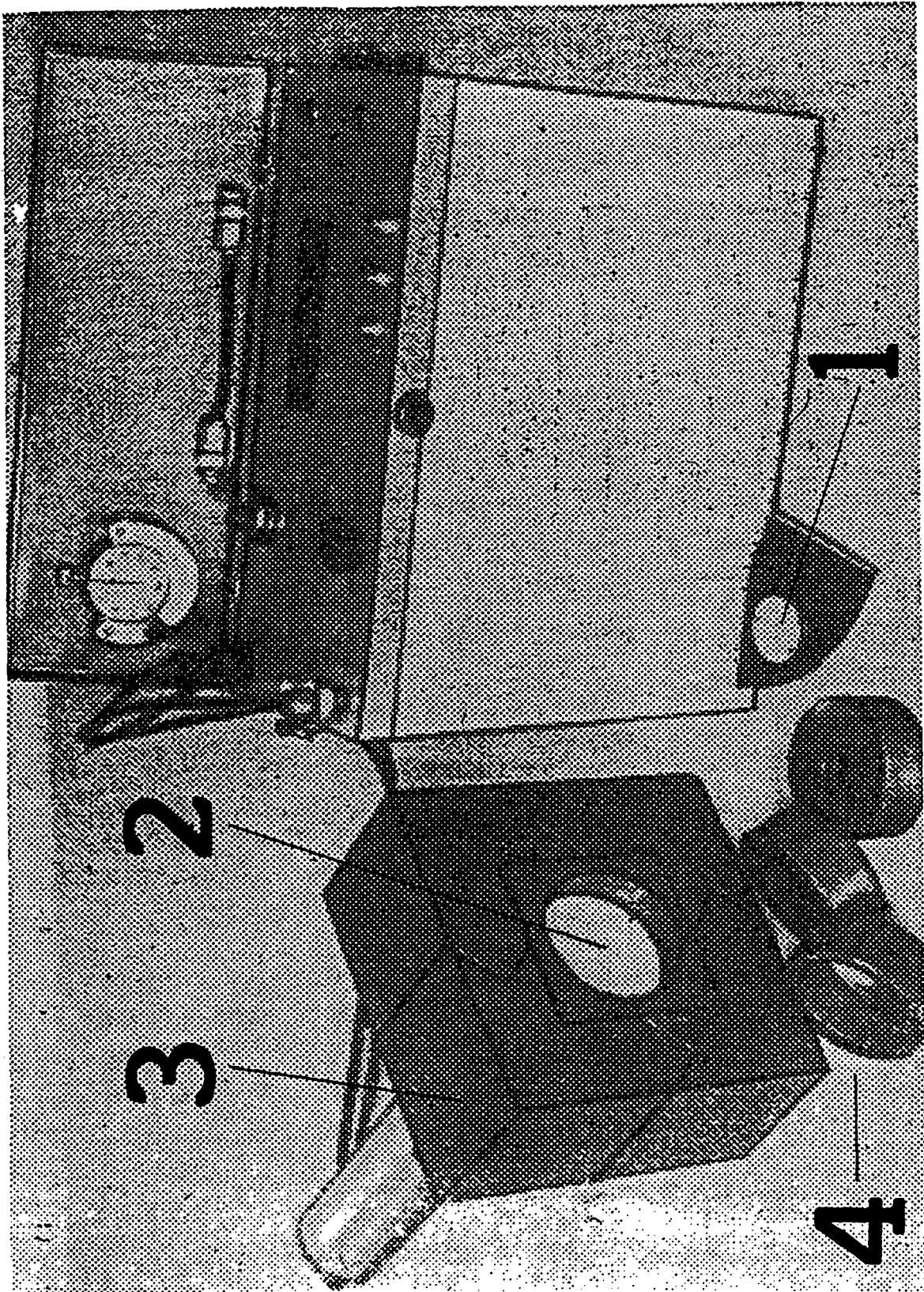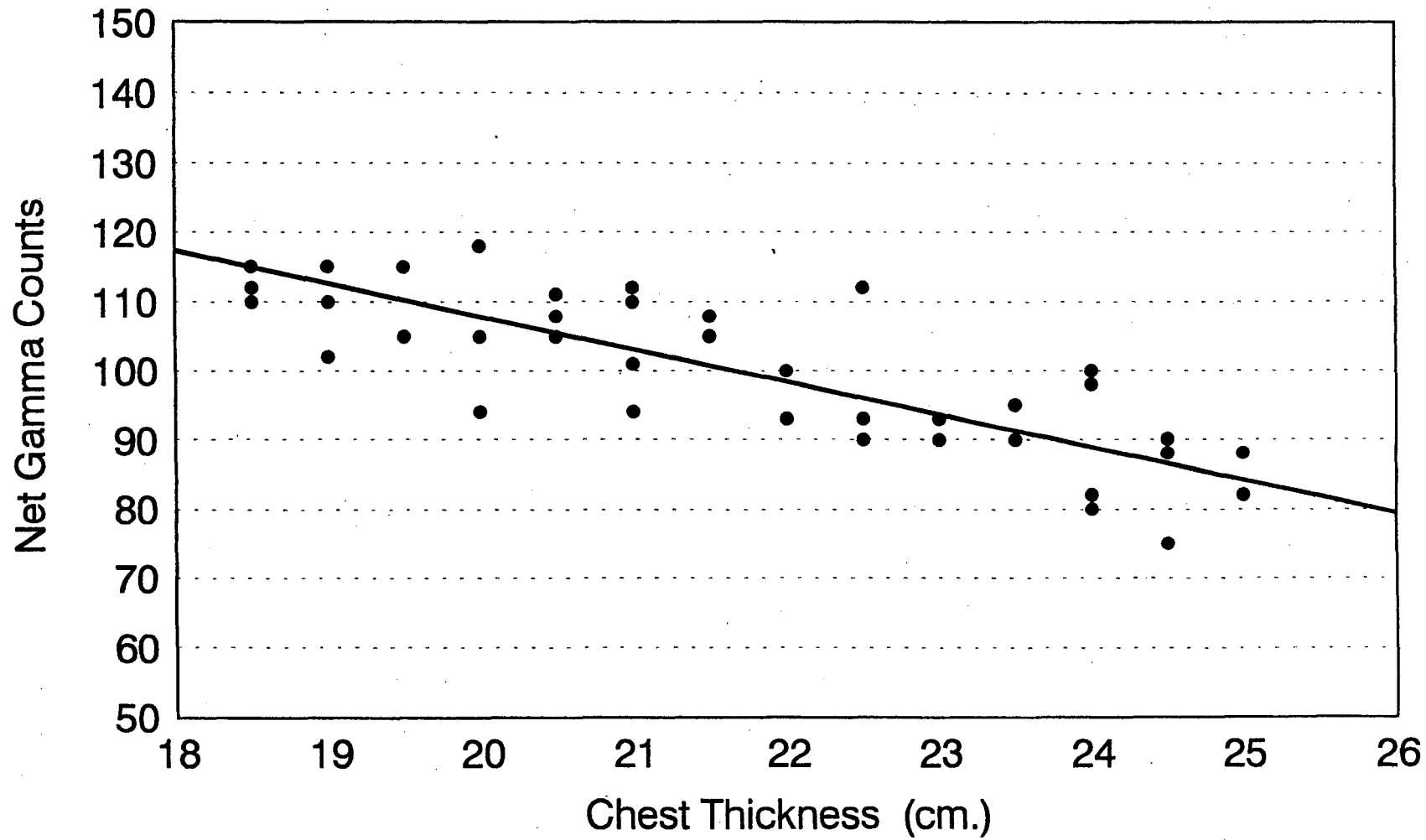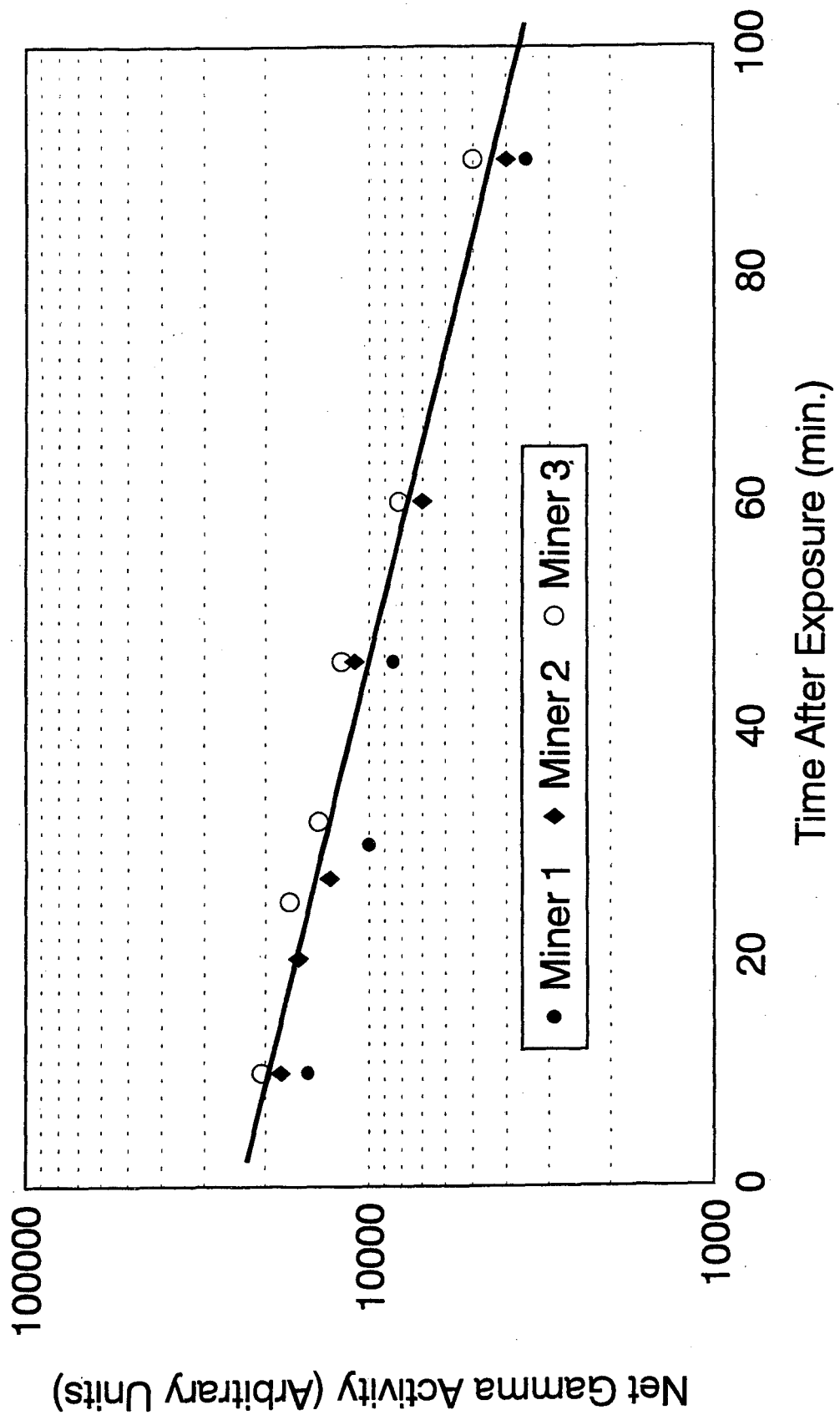
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