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Magnetic measurements of pulmonary contamination

by PIRKKO-LIISA KALLIOMÄKI, M.D., L.Sc. (Eng.),¹ PEKKA J. KARP, M.Sc. (Eng.),² TOIVO KATILA, D.Tech.,² PENTTI MÄKIPÄÄ, M.Sc. (Eng.),² PEKKA SAAR, M.D.,^{2, 3} and ANTTI TOSSAVAINEN, L.Sc. (Eng.)¹

KALLIOMÄKI, P.-L., KARP, P. J., KATILA, T., MÄKIPÄÄ, P., SAAR, P. and TOSSAVAINEN, A. Magnetic measurements of pulmonary contamination. *Scand. j. work environ. & health* 4 (1976) 232—239. The magnetic determination of pulmonary contamination is based on the remanent magnetization of ferromagnetic contaminating particles. The remanent field of the externally magnetized particles is proportional to their amount and shows their distribution. Although only magnetizable particles are detected with this method, the amount of the inhaled ferromagnetic substance can be used when the total dust exposure of the worker is estimated. In this work five shipyard welders were studied. First the particles deposited to the lungs were externally magnetized and then their distribution was mapped with a sensitive magnetometer. The magnitudes of the remanent fields measured from the welders differed from the fields measured from controls by several orders of magnitude. The radiographic findings showed a good correlation with the magnetic measurements, and further experiments will prove whether this method can partly replace presently used radiological investigations.

Key words: ferromagnetic contamination, welders, lung function.

The deposition of foreign particles in pulmonary tissue has in the past been measured primarily with radioactive tracer techniques. Because human tissue is mainly diamagnetic, ferromagnetic particles deposited in the pulmonary area can also be detected with a suitable magnetic measuring method.

The arc welding of iron or steel produces airborne ferromagnetic compounds such as magnetite (Fe_3O_4).⁴ The iron oxides retained in the lungs of welders are respon-

sible for the development of a fibrosing pneumoconiosis known as pulmonary siderosis. Because the actual accumulation of iron dusts and fumes in the lungs during chronic exposure is important in the development of a health hazard, a magnetic measurement of pulmonary contamination, in connection with lung function tests and chest radiographs, was performed on five arc welders from a shipyard.

Previously, the magnetic method had been applied only by D. Cohen (1,2). A technique which resembles the one used by Cohen in many respects is utilized in this study.

This work was carried out as a joint project of the Institute of Occupational Health and the Helsinki University of Technology, where research on biomagnetic fields has been performed since 1973 (3, 4).

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⁴ Fe_3O_4 is actually ferrimagnetic.

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MATERIAL

The subjects were five arc welders (W I...W V) from a shipyard in Helsinki who had worked as arc welders in shipyards for more than 10 years. They used basic coated electrodes to weld mild steel. They had worked in open workshops as well as in confined spaces in ships.

The welders' annual health examination served as the clinical examination. During the interview, they were questioned about the total time they had spent as welders, as well as about the amount of exposure during preceding months. They were also asked whether they had experienced any respiratory symptoms and were requested to evaluate their own levels of physical performance. The following laboratory tests were performed: hemoglobin, hematocrit, MCV, MCHC, the erythrocyte sedimentation rate, U-Alb, U-Gluc, urinary δ -aminolevulinic acid, and blood lead level, and chest radiographs were taken. Spirometry, capnography, and the transfer factor were used to evaluate respiratory function.

METHODS

The magnetic determination of ferromagnetic contamination is based on the measurement of the remanent field of magnetized particles within the body. The measurement procedure is the following: First the pulmonary area of the subject is magnetized in an external magnetic field. During the magnetization the subject stands between a pair of Helmholtz coils as shown in fig. 1. The magnetizing field is perpendicular to the frontal plane and its magnitude is 0.02 T.⁵ The duration of the magnetization is 5 min. After the magnetization the remanent field of the pulmonary area is mapped as shown in fig. 2.

In the earth's magnetic field the diamagnetic susceptibility of the body gives rise to a small signal (appendix), which is eliminated when a second measurement of the remanent field is made with the direction of the magnetizing field inverted.

⁵ The unit magnetic flux density is the tesla (T). 1 T = 10^4 gauss, 1 nT = 10^{-9} T = 10^{-5} gauss.

Fig. 1. The magnetization of a subject.

Fig. 2. Measurement of the remanent field.

The diamagnetic signal then disappears from the difference of the two measurements, and this difference is used as the final result.

The remanent field is measured in 5×5 grid points, which are shown in fig. 3. The uppermost row is placed at the upper sternal edge, while row D is at the xiphoid. Columns 1 and 5 lie on the mamillary lines. Fig. 5 shows the distribution of the remanent field along row B of an arc welder. The distribution obtained from a control is a practically straight line. In most mappings the horizontal displacement was interrupted at each grid point. The time required for one mapping was usually less than 10 min.

A magnetometer that is to be used in these measurements must have a high sensitivity, satisfactory spatial resolution, and a frequency response down to steady fields. A superconducting SQUID magnetometer was used in the present study;

it operates at the temperature of liquid helium (4 K). The sensitivity of this detector is $2 \cdot 10^{-5}$ nT, which is much better than the minimum resolution required.

For comparison a few measurements were also made with a conventional flux-gate magnetometer, the sensitivity of which is typically 0.1 nT. In cases with fairly heavy ferromagnetic contamination the mapping could be performed with this easy-to-use room-temperature magnetometer. In preliminary measurements, however, the superconducting magnetometer was used to achieve a better accuracy and resolution, especially in the case of nonexposed subjects.

RESULTS

The average signal measured from the pulmonary area of the control group was 0.02 nT (fig. 3). As the controls were supposedly free from ferromagnetic material in this area, the signal represents the error of the method. In the pulmonary area the magnitude of the signals varied randomly. The systematically larger signals from the abdominal area are

presumably related to ingested food.

All results from the welders showed a distinct concentration of a strong remanent field in the pulmonary area (fig. 4). Because of the asymmetric pulmonary volumes the signals from the right lung tended to be slightly stronger than those from the left lung. The largest remanent fields were measured from subject W III, whose maximum signal on the central area of the right lung was 100 nT. The lowest fields were obtained from subject W V, but even his signals were of the order of 10 nT, which is still 1,000 times larger than the remanent fields on the pulmonary area of the controls.

Because the signals from the welders were at least three orders of magnitude larger than the signals from the controls, we are convinced that they were caused by ferromagnetic material accumulated in the lungs. Separate measurements from the exposed skin areas confirmed that the magnetized material was not localized on the skin.

The measured remanent field on a given grid point is not only related to the amount of ferromagnetic material located under the magnetometer, but also includes

Fig. 3. The remanent fields of the controls. The areas of the circles are proportional to the measured signal. The black dots represent remanent fields with the same direction as the magnetizing field, and the white dots represent remanent fields opposite to the direction of the magnetizing field. Note that a given circle area in fig. 4 represents 100 times as much remanent field as in fig. 3. The average magnetic field of the three controls varied from 0.0036 nT to 0.004 nT.

Fig. 4. The remanent fields of the welders. The average magnetic field varied from 2 nT to 33 nT.

smaller contributions from other sources of magnetic fields. For instance, in fig. 5 the minimum of the curve in the middle of the lungs is elevated by this effect. The lower part of fig. 5 represents a transverse section of the thorax, and in the upper part appears the distribution of the measured remanent field in this plane.

When a suitable model is assumed, it is possible to calculate the real distribution of the ferromagnetic material from the measured distribution of the remanent field.

After magnetization, the remanent magnetic field shows a characteristic time

Fig. 5. The remanent magnetization in one transsectional plane.

dependence (relaxation). Fig. 6 illustrates this relaxation phenomenon. The measurement was started 5 min after the magnetization (the subject is W III). The signal decreased to 50 % of the initial value in about 25 min. Possible causes of the relaxation are the movements of the particles in the lung tissue and changes in the magnetization of the particles.

The relevant anamnestic and clinical findings, together with the measured average magnetic field (AMF)⁶, are listed in table 1. The blood and urine tests were normal and the welders evaluated their physical performance as normal.

The chest radiographs were graded as follows: 0 = normal; 1 = distinct, fine mottling localized in the central parts of the lungs; 2 = more distinct and clear-cut mottling involving more than the central parts of the lungs; and 3 = uniformly distributed generalized distinct mottling involving both lungs. (The last finding is indicative of siderosis.) No other pathological changes were seen in the chest radiographs of the subjects. The health of the subjects was relatively good. No evident relationship between exposure time and the AMF could be seen. However, the agreement between the radiograph grading and the AMF is obvious.

DISCUSSION

The accuracy and precision of the magnetic measurements form the basis for drawing any conclusions from this study. The sources of measurement error include the following: (a) the inhomogeneity of the magnetizing field, (b) the dependence of the remanent magnetization on time, (c) the variation of the distance between the subject and the detector, (d) the inaccuracy of the measurements of the magnetic field, and (e) the dependence of the initial remanent magnetization on the magnetization time.

Experimentally, the measurement error was estimated in two different ways. The error in the measurement of the magnetic

⁶ $AMF = \frac{\sum_i B_i}{N} = \bar{B}$, where B_i is the signal in grid point i and N is the number of grid points.

Fig. 6. The relaxation of the remanent field.

field was estimated from the scatter of the results from the controls. The diamagnetic response of the body to the earth's magnetic field generates a diamagnetic field of about 0.04 nT (fig. 7 and appendix). A measurement accuracy of better than 0.02 nT can easily be achieved. Compared with the much bigger fields measured from the welders, this error is negligible.

In order to study the reproducibility of the method, we measured every welder again two days later. The average difference between the measured fields in the middle of the chest was about 10 %. This difference was probably caused primarily by inaccuracies in locating the detector.

The influence of breathing and the functioning of the heart on the measured magnetic field is shown in fig. 8. The amplitude variation caused by breathing averaged 2 nT; and that from cardiac activity, 0.3 nT for this subject.

We feel confident that if a more accurate measurement of the field were needed, substantial improvements could be made by a more careful control of the position of the subject during the magnetization and the measurements.

In fig. 7 the magnitudes of the measured remanent magnetic fields from the five welders are shown on a logarithmic scale, together with the magnitude and measurement error of the diamagnetic field and the magnitude of the field sometimes found in the vicinity of the stomach. This figure illustrates the enormous difference between the fields obtained from the welders and from normal subjects.

Table 1. Clinical data.

Subject	Age (years)	Exposure time (years)	Clinical findings	Smoking (years)	Respiratory function			Radio-graph grading ^a	AMF ^b (nT)
					Spirometry	Capnography	Transfer factor		
W I	43	19	—	20	normal	normal	normal	2	7
W II	45	22	elevated respiration rate since 1972	—	mild. restriction	normal	normal	2	10
W III	37	13	—	—	normal	normal	normal	3	33
W IV	40	17	siderosis since 1971	—	normal	slightly abnormal	normal	3	30
W V	46	21	—	20	normal	normal	normal	1	2

^a 0 = normal; 1 = distinct, fine mottling localized in the central parts of the lungs; 2 = more distinct and clear-cut mottling involving more than the central parts of the lungs; and 3 = uniformly distributed generalized distinct mottling involving both lungs (This finding is indicative of siderosis).

^b AMF = average magnetic field.

Fig. 7. The magnitudes of measured signals. F indicates the sensitivity of a flux-gate magnetometer. The result from an asbestosis patient is shown for comparison.

Fig. 8. The effects of respiratory and cardiac activity.

The present method can be applied in follow-up studies of the pulmonary clearance rate. Magnetic measurements would be especially suitable for screening purposes since the number of radiographic

examinations and the associated radiation hazard could be reduced.

Furthermore, the distribution of accumulated ferromagnetic material can be mapped. An abnormal distribution might reveal local pulmonary injuries or functional disturbances. The condition of the pulmonary system is currently evaluated with radioactive markers and radiographs with contrast material. With improved local magnetometer resolution, the magnetic method may prove to have clinical applications, especially in occupational medicine.

Immediately after the magnetization, the remanent field decreases rapidly, as shown in fig. 6. This effect, called relaxation by Cohen, depends on the mechanical forces exerted on the particles, and pulmonary movements contribute to these forces. Because different pulmonary diseases change the mechanical properties of the pulmonary tissue in characteristic ways, it seems possible that pulmonary disorders may be associated with characteristic relaxation rates. Specific pulmonary disorders may also be identifiable by the accumulation and clearance rates of harmless magnetic dusts in short-time exposure tests (2).

In summary, the magnetic measurement of pulmonary contamination seems to be a promising tool in occupational medicine as well as a new method for evaluating pulmonary function.

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APPENDIX

Magnetic ellipsoid in a homogeneous magnetic field

In the calculation of the influence of a diamagnetic body on the measured remanent field, the torso is assumed to be a homogeneous ellipsoid with the semiprincipal axes $a = 30$ cm, $b = 20$ cm, and $c = 12.5$ cm. The external magnetic field (the vertical component of the earth's magnetic field) H_0 is assumed to be perpendicular to the ab -plane.

Outside the ellipsoid, the magnetic scalar potential associated with the magnetic field H_0 is the following (5):

$$\varphi_m = \varphi_0 \frac{1 + \frac{abc}{2} \frac{\mu_1 - \mu_2}{\mu_2} \int_0^\xi \frac{ds}{(s + c^2)R_s}}{1 + \frac{abc}{2} \frac{\mu_1 - \mu_2}{\mu_2} \int_0^\infty \frac{ds}{(s + c^2)R}} = \varphi_0 + \varphi_d, \quad (\text{A } 1)$$

where $\varphi_0 = -H_0 z$, $R_s = [(s + a^2)(s + b^2)(s + c^2)]^{1/2}$, and φ_d is the disturbance due to the ellipsoid. One can obtain the magnetic field from its scalar potential (A 1) by writing

$$\vec{H} = -\nabla\varphi_m = H_0\vec{k} - \nabla\varphi_d = H_0\vec{k} + \vec{H}_d \quad (A\ 2)$$

With some algebra the disturbance part of equation A2 can be solved:

$$\begin{aligned} H_d(x,y,z) = C \bigg\{ & \left[\frac{(\xi + a^2)(\xi + b^2)(\eta + c^2)(\zeta + c^2)}{(\xi - \eta)(\xi - \zeta)} \right]^{1/2} \int_{\xi}^{\infty} \frac{ds}{(s + c^2)R_s} \\ & - 2 \left[\frac{(\eta + c^2)(\zeta + c^2)}{(\xi - \eta)(\xi - \zeta)(\xi + c^2)} \right]^{1/2} \bigg\} \frac{2z}{(\xi + c^2) \|i_1\|} + \\ & + \left\{ \left[\frac{(\eta + a^2)(\eta + b^2)(\xi + c^2)(\zeta + c^2)}{(\eta - \zeta)(\eta - \xi)} \right]^{1/2} \int_{\xi}^{\infty} \frac{ds}{(s + c^2)R_s} \right\} \frac{2z}{(\eta + c^2) \|i_2\|} \bigg\}, \quad (A\ 3) \end{aligned}$$

where $C = -\frac{abc \cdot K \cdot H_0}{2 \left[(a^2 - c^2)(b^2 - c^2) \right]^{1/2} \left[1 + \frac{abc}{2} K \int_0^{\infty} \frac{ds}{(s + c^2)R_s} \right]}$,

$$\begin{aligned} \|i_1\| &= \left[\left(\frac{2y}{\xi + b^2} \right)^2 + \left(\frac{2z}{\xi + c^2} \right)^2 \right]^{1/2}, \\ \|i_2\| &= \left[\left(\frac{2y}{\eta + b^2} \right)^2 + \left(\frac{2z}{\eta + c^2} \right)^2 \right]^{1/2}, \end{aligned}$$

ξ, η and ζ are the elliptic coordinates and K is the susceptibility of the ellipsoid.

Equation A3 can be used to plot the disturbance field H_d in one transverse section of the ellipsoid (the section containing the semiprincipal axes b and c) at a distance of 14.5 cm from the b -axis. The result of this calculation is shown in the figure below. The average susceptibility of the thorax area can be estimated to be about twice the susceptibility of water. Then the calculated diamagnetic effect in the figure agrees well with the measured value shown in fig. 7 of the text.