Non-invasive magnetopneumographic determination of lung dust loads in steel arc welders

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ABSTRACT Magnetopneumography was used to measure non-invasively the concentration of the ferrimagnetic fraction of retained welding fume in the thoraces of steel arc welders. This was done by measuring the remanent magnetic fields due to ferrimagnetic particles. The 11 welders studied had concentrations of thoracic ferrimagnetic mineral several orders of magnitude greater than three machinists, 16 former asbestos insulators, and 24 control subjects. These concentrations correlated well with total years welding ($p < 0.01$) and radiographic evidence of small rounded densities ($p < 0.05$), but not with smoking history. There was a higher concentration of ferrimagnetic mineral over the hilar regions. Magnetopneumography offers a non-invasive indicator of the accumulation of welding fume in the thorax.

Magnetopneumography is a non-invasive technique for detecting the presence and location of magnetic dust particles retained in the thorax.¹ The randomly orientated magnetic moments of these particles are first aligned by an external magnet and then measured with a sensitive magnetometer adjacent to the chest. Welding fume may contain 25-70% magnetite ($\text{FeO} \cdot \text{Fe}_2\text{O}_3$), a strongly ferrimagnetic compound.² By contrast, endogenous organic compounds, including those containing iron, have not been found to have significant ferrimagnetic properties and therefore do not contribute to the remanent magnetic field over the thorax (D E Farrell, personal communication).

The detection of ferrimagnetic minerals (FM) in the thorax by their permanent magnetic properties was first reported by Cohen^{3,4} and subsequently studied by Kalliomäki¹ and by Kalliomäki *et al*⁵⁻⁷ and by our group⁸⁻¹⁰ in welders, foundry workers, asbestos miners, and coal workers. Although the major FM in welding fume, magnetite, is considered non-toxic,¹¹ it serves as a magnetic tracer for the other constituents of the fume.

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We performed this study of FM concentrations in steel arc welders to evaluate the potential role of magnetopneumography in monitoring pulmonary accumulation of welding fume.

Methods

MAGNETOPNEUMOGRAPHY

The apparatus used for magnetopneumography consisted of a pair of large electromagnetic coils for magnetisation and a separate superconducting magnetometer for measuring remanent fields. The electromagnet generated a uniform and parallel magnetising field of 36 milliTesla between the coils. With the subject standing within the electromagnet, the field was applied normal to the frontal plane of the chest for 15 seconds. This aligned the magnetic moments of ferrimagnetic particles. Respiratory motion eventually randomised this induced magnetic orientation, reducing remanent fields by half within 10-30 minutes. The safety of much larger magnetic fields applied over a longer period of time is accepted.^{12,13}

Remanent magnetic fields were measured with a superconducting biomedical gradiometer (SHE Corporation) using a SQUID sensor (superconducting quantum interference device).¹⁴ As the gradiometer (or differential magnetometer) assured relative insensitivity to background ambient magnetic noise shielding was unnecessary. This instrument had

Fig 1 Anterior chest grid used consisted of 35 locations spaced at 5 cm intervals. Location E-3 was aligned at the xyphoid process.

resolution to 1 picoTesla. Remanent magnetic fields were measured normal to the anterior chest at 35 locations spaced on a 5×5 cm grid to allow representative measurements of various regions of the thorax (fig 1). At each location, the background field recorded distant from the chest was subtracted from the magnetic field recorded with the probe adjacent to the chest to give a true reading of the body's magnetic field. The entire mapping was completed in 10 to 15 minutes.

The body's magnetic field includes not only remanent field from FM, but components from endogenous ion currents and from the body's local attenuation of the earth's magnetic field (diamagnetic susceptibility of tissue).¹ These components are relatively small (< 40 picoTesla) and are unrelated to the magnetising field. If recorded fields were less than 200 picoTesla, the remanent field due to FM was distinguished from these other components of the body's magnetic field by its dependence on the polarity of the magnetising field. A second mapping at all 35 locations was then performed after remagnetisation with opposite polarity. The remanent field from FM reverses polarity and is numerically equal to half the difference between the first and second measurements at each point.⁸

If the map of remanent fields suggested a strong extrathoracic magnetic source such as orthopaedic steel hardware or non-removable dental appliances, a bulk-tape eraser was used to demagnetise the source before remeasurement.

All volunteer subjects reported to the laboratory after showering and donning freshly laundered

clothes. They were instructed not to use talc, as it contains some magnetic contaminant. No food or drink was permitted for three hours before measurement to minimise the magnetic artifact resulting from ingested particles or the gastric secretory ion current. An informed consent was obtained from each subject.

CALCULATION OF FERRIMAGNETIC MINERAL CONCENTRATION

The concentration of FM in the thorax was derived from measured remanent fields using as a first approximation the linear relationship assumed by Cohen.⁴ Peak sensitivity of 5 nanograms of magnetite/cc/picoTesla remanent field for our gradiometer with this magnetising field was determined by measuring phantom lung models. Average thoracic FM concentration was obtained by averaging values at coordinates from A-1 to F-5. Similarly, values at coordinates C-2 and C-4 or D-2 and D-4, whichever had the highest sum, were averaged to derive a crude index of hilar FM concentration. Anomalous points of "negative polarity" (regions in which the remanent field polarity is opposite that of the magnetising field), shown to be a consequence of geometric mismatching of magnetising and sensing coils, were not included and are discussed below.¹⁵

POPULATION STUDIED

Our study population consisted of 11 active electric-arc welders from a local shipyard. Their ages ranged from 25 to 62 and they had had from six to 40 years welding experience. Three machinists from the same shipyard, 16 former asbestos insulators from the same geographical area, and 24 rural men with no occupational exposure to FM served as controls.

Chest radiographs were graded blind according to the UC/ILO classification by a B-reader (LG). All chest radiographs were taken within several months of measurement.

STATISTICAL ANALYSIS

Data were analysed for statistical significance using Spearman's rank correlation.

Results

Averaged thoracic remanent fields in the 11 welders ranged from 79 to 22 000 picoTesla (pT) with a geometric mean of 2111 pT (table). Using the calibration factor of 5 ng magnetite/cc/pT and assuming thoracic volumes of 7 litres, the estimated thoracic FM content ranged from 3 to 777 mg. This is actually an underestimate, as discussed below.

Averaged thoracic remanent fields for the three machinists ranged from 2 to 14 pT. Averaged

Clinical and magnetopneumographic data

Arc welders	Average thoracic remanent fields	Estimated ferrimagnetic mineral	Hilar remanent fields	Chest radiograph (UC/ILO)	Years welding	Pack-years smoking
1	22 200	777	37 200	1/1q	33	—
2	11 360	398	18 750	0/0	17	—
3	4 530	159	9 000	1/1p	10	4
4	4 350	152	8 200	3/3p	33	65
5	3 620	127	11 100	0/1p	15	35
6	1 605	56	3 875	1/0p	12	2
7	1 552	54	900	1/1p	13	—
8	1 475	52	2 343	0/1p	6.5	9
9	1 125	39	2 367	0/0	10	40
10	630	22	1 134	0/0	6	12
11	79	3	153	0/0	40*	96

*Instructor.

Fig 2 Averaged thoracic remanent magnetic fields over anterior chests of workers. A log scale is used to accommodate high values obtained in arc welders.

thoracic remanent fields for the 16 asbestos insulators were 6.4 ± 5.6 pT (arithmetic mean $\pm$ standard deviation) and those of the 24 rural subjects were 4.7 ± 1.9 pT (fig 2).

Thoracic content of FM in the welders correlated well with total years worked ($p < 0.01$) when the

Fig 3 Remanent field maps over anterior chest. Largest values are recorded centrally over path of lymphatic drainage to hilum. Negative values, remanent fields opposite in polarity to magnetising field, are an artifact of uniform-field technique used.

instructor was excluded from analysis. He was a welder for 40 years, but had been minimally exposed over the past five years. FM content was highest in those manifesting radiographic evidence of small p, q, r rounded opacities ($p < 0.05$). There was no correlation between FM levels and smoking history.

Assessment of the distribution of FM showed a predominance over the central thoracic or hilar regions. The two magnetopneumographic maps (fig 3) show this pattern of distribution.

Discussion

Thoracic remanent fields in the welders were several orders of magnitude above those of machinists, asbestos insulators, and rural subjects. The values obtained are comparable to magnetic data on welders reported by Kalliomäki *et al.*^{5,6} Thoracic FM content correlated well with years welding in our group ($p < 0.01$). The lack of even better correlation in these welders most likely reflects differing exposure levels, work habits, and dust clearance kinetics. Thoracic FM content showed no correlation with smoking history in the welders, an unexpected finding in view of the reported effects of cigarette smoking on the long-term clearance of particles from the lung.¹⁶

The occurrence of radiographic changes suggestive of haemosiderosis in those welders with the highest FM contents is not surprising. What is more interesting is the ability of magnetopneumography to detect dust accumulation in welders without radiographic changes, suggesting that magnetopneumography is a much more sensitive indicator of welding fume than the chest radiograph.

There was a pronounced increase in remanent field centrally, over the hilar regions. This pattern is in agreement with the expected translocation of particles deposited in non-ciliated alveolar regions towards the central lymphatics.^{17,18} Lymph nodes have been shown to have up to ten times the dust concentration of lung tissue.¹⁹⁻²¹ Hilar concentration of dust was evident magnetopneumographically despite the relative insensitivity of our current technique to deep structures.

What exactly are we detecting? It is highly unlikely that a significant portion, if any, of the remanent field measured derives from endogenous substances rather than the FM in retained dust. Ferrimagnetic compounds are not known to be found in the body. Haem and ferritin have paramagnetic properties but do not hold a significant remanent field (D E Farrell, personal communication). The asbestos insulators we studied had a high prevalence of interstitial and pleural fibrosis and undoubtedly had many ferruginous bodies, yet had low remanent fields. Therefore,

the possibility of endogenous material accounting for the very large remanent fields of welders is remote.

How accurately do remanent fields reflect tissue concentrations of FM? Although the uniform-field method used for magnetopneumography was based largely on the established techniques,^{1,3-7,16} our studies of phantom lung models have identified several factors affecting the accuracy of FM measurement. The remanent magnetic field over a given location is not merely proportional to the concentration of FM below it. It is also dependent on lung geometry, the magnetising field, sensing coil configuration, and the distribution of FM.¹⁵ FM is usually underestimated with uniform-field magnetopneumography, due to cancellation by the return magnetic flux from adjacent particles. With a homogeneous distribution of FM, remanent fields are largest over the boundaries of the measured objects and very small over the central regions. When the distribution of FM is not homogenous, large remanent fields are seen over areas of higher FM concentration while surrounding areas of lower FM concentration have remanent fields that are smaller than expected or even opposite in polarity to the magnetising field ("negative"). Though the remanent field map may be distorted by this effect, regions with high FM concentration such as the hilar lymphatics will still be clearly seen. FM concentrations in this study are therefore only estimates. A modification termed localised-field magnetopneumography, however, has the potential for quantitative measurements.¹⁵

How well does magnetopneumographic determination of FM indicate welding fume accumulation? FM concentration is proportional to overall dust content only if there is a fixed fraction of FM in the inhaled dust and the FM deposited is cleared at the same rate as the rest of the dust. In cross-sectional studies employing single measurements, calculations of thoracic welding fume content serve only as estimates. If serial measurements of thoracic FM are supplemented by measurements of FM concentration in the welding fume to which a given worker is exposed, however, thoracic welding fume content can be accurately calculated.

From this preliminary study, it appears that magnetopneumographic determination of thoracic FM provides a non-invasive index of thoracic welding fume content and has the potential for full quantitation. This can greatly simplify studies of the health effects of exposure to welding fume as lung dust content is a better measure of cumulative exposure than work history. Furthermore, magnetopneumography can be used to monitor the rate of dust accumulation in the lung.

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