THE INHALATION OF FIBRES

V. TIMBRELL
Pneumoconiosis Research Unit of the Medical Research Council, Penarth, Glamorgan, U.K.

A previous study (Timbrell, 1965) examined the influence of the diameter and length of fibres on the respirability of these particles. This paper extends the discussion to the influence of the fibre shape, with specific reference to the relative respirability of chrysotile and amphibole asbestos.

PARTICLE DEPOSITION MECHANISMS

The mechanisms operating to deposit particles in the lung and the relevant particle parameters are:

i. Gravitational settlement: free falling speed.
ii. Inertial impaction: proportional to free falling speed.
iii. Interception: size.
iv. Diffusion: size.

Diffusion is efficient only for particles smaller than 0.5 microns in small air spaces and is of little importance for the long fibres that can penetrate deeply into the lung.

FIBRE DIAMETER

The observation that fibres of a range of different materials recovered from lungs are very slender is explained by the fact that the free falling speed of a fibre is approximately proportional to the diameter squared and almost independent of the length. Only if a fibre is of small diameter can it avoid deposition from gravitational settlement and inertial impaction high in the respiratory tract and succeed in penetrating to the pulmonary air spaces.

Fibres of amphibole asbestos (amosite, anthophyllite and crocidolite) found in lungs are straight and have a maximum diameter of about 3 microns (Timbrell, Pooley and Wagner, this Conference, p. 120). Chrysotile fibres, on the other hand, are often partially opened bundles of very fine fibrils, whose length and diameter are difficult to define. When, however, chrysotile fibres in lung sections are tight bundles, the maximum diameter of these is approximately the same as for the amphiboles. Aerosol spectrometer examinations of partially opened bundles and aggregates of chrysotile fibres have shown that some of these can have low falling speeds for their size. This explains why 'thick' chrysotile fibres are sometimes found in lungs.

FIBRE LENGTH

For particles of compact shape, such as those of coal and silica, the important deposition mechanisms operating in the upper respiratory tract are gravitational settlement and inertial impaction. Only if these compact particles are less than about 10 microns in diameter can they penetrate deeply into the lung. Even the largest of these particles is small compared with the diameters of the narrow airways so that interception, which depends on the relative sizes of particle and airway diameter, is of little consequence.

For fibres, however, interception can be very important. A long fibre, if it is slender, may avoid deposition in the upper respiratory tract from gravitational settlement and inertial impaction and penetrate deeply to the pulmonary air spaces. In these regions the length of the fibre may be comparable to the diameters of the airways, and interception becomes a major deposition mechanism.

The previous study showed that the efficiency of deposition of fibres by interception increases with increase in fibre length and with decrease in airway diameter. Interception must be expected to concentrate long fibres in the narrow air ducts and particularly at bifurcations. Elsewhere at this Conference (Timbrell, Pooley and Wagner, p. 120) the length distributions of amosite fibres in rat lung sections are compared with the length distribution of the fibres to which the animals were exposed. These results show that fibres 50 microns and longer were present in the lungs: the fibres in the lung were on average shorter than those in the cloud and the longer fibres were mainly in the narrow air ducts, particularly at bifurcations. Although other factors were probably involved the results agree with the conclusions reached from analysis of the interception effect in the previous study.

FIBRE SHAPE

The most striking physical difference between the 2 main types of asbestos fibres is their shape: the amphiboles are straight and the chrysotiles curly, roughly resembling a stretched coil. This suggests the possibility of important differences between the magnitudes of the size-sensitive interception effects in

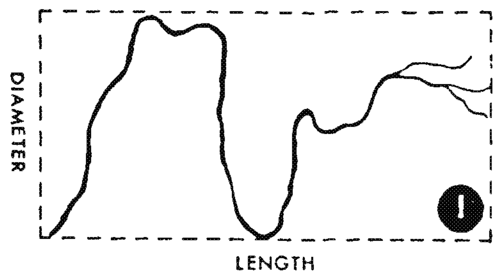

Fig. 1. Measurement of coil diameter and coil length of a curly fibre.

the lung for the 2 types of fibre. Data have therefore been collected on the shape as well as the size of fibres in industrial clouds of amphiboles and chrysotile and in clouds generated under laboratory conditions.

A complete mathematical description of the shape of a curly fibre is difficult but a simple definition is adequate for present purposes. The coil is enclosed in an imaginary cylinder. Under the microscope this cylinder normally has its axis parallel to the surface of the slide or membrane filter on which it is lying. A rectangle is visualized around the microscope image of the fibre as illustrated in Fig. 1. and the width and length are measured. These 2 dimensions represent approximately the diameter and length of the cylinder enclosing the coil. The ratio of coil diameter and coil length is referred to as the 'coil aspect ratio'. The ratio of the diameter and length of the fibre remains the 'aspect ratio'. It may be noted that if the fibre is

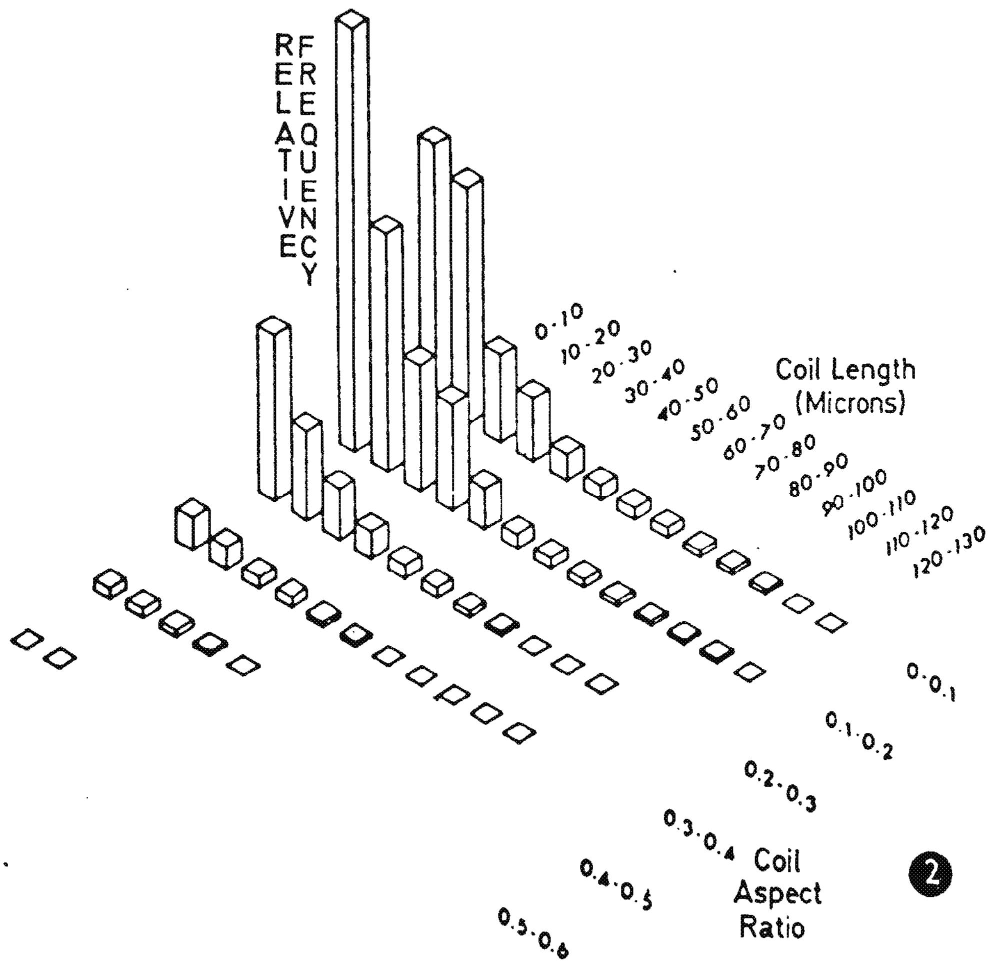

Fig. 2. Distribution of coil length and coil aspect ratio for UICC Rhodesian chrysotile.

straight the coil aspect ratio is equal to the aspect ratio.

Fig. 2 shows the joint distribution of fibre coil length and coil aspect ratio obtained from a membrane filter sample of the UICC Rhodesian chrysotile reference sample; Fig. 3 shows the distribution for an industrial cloud of chrysotile. Although these distributions differ in detail, they both exhibit the characteristic of a relatively small proportion of fibres with coil aspect ratio < 0.1: in both clouds the proportion of fibres that could be described as straight was even smaller.

Fig. 4 shows examples of distributions of coil length and coil aspect ratio of laboratory and industrial clouds of amphibole fibres. Because these fibres were straight the majority of the coil aspect ratios were low (< 0.05), compared with the much higher ratios for the chrysotile fibres.

Fibre Shape and the Interception Effect

In the study mentioned earlier, in order that the calculations should produce conclusions applicable to asbestos fibres in general, it was supposed that the fibres were straight and had random orientation in airways. This was justifiable on the grounds that asbestos fibres are often dirty and that orientation is markedly influenced by attached particles. It was pointed out however that in practice, penetration of straight fibres into the respiratory tract would be assisted by a marked tendency for such fibres to align themselves parallel to the axis of an airway:

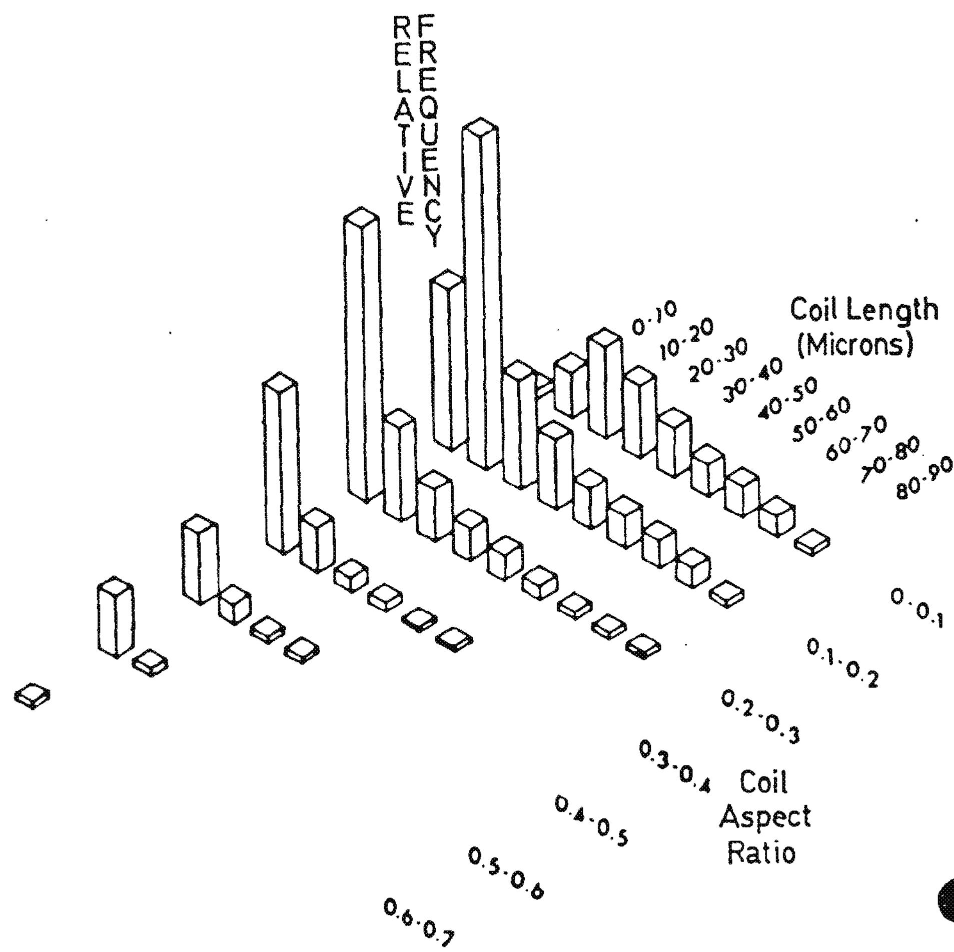

Fig. 3. Distribution of coil length and coil aspect ratio for an industrial chrysotile.

this tendency is the greater the longer the fibre and the smaller the airway diameter.

If a straight fibre has such an orientation in an air duct, the effective interception diameter can be as small as the actual diameter of the fibre, and if the air duct is one of the narrower airways this diameter must be less than about 3 microns for the fibre to succeed in reaching the region. This makes it possible for a fibre 100-microns long to have an interception diameter of 3 microns or less. Fig. 4 shows that virtually all the fibres in the amphibole clouds could have small interception diameters in the narrow lung airways.

fibre has to settle to make contact with the wall of an airway. The influence of curvature on the orientation of a fibre could result in this distance being shortened by as much as half the length of the fibre: for long fibres in narrow airways the reduction could be substantial.

Curvature in a fibre therefore works to decrease the efficiency of penetration, especially in narrow airways. Looked at in another way, introduction of curvature into a fibre causes deposition to be earlier and the site to be higher in the respiratory tract. The fibres most affected are the long fibres, which are also in general the most massive.

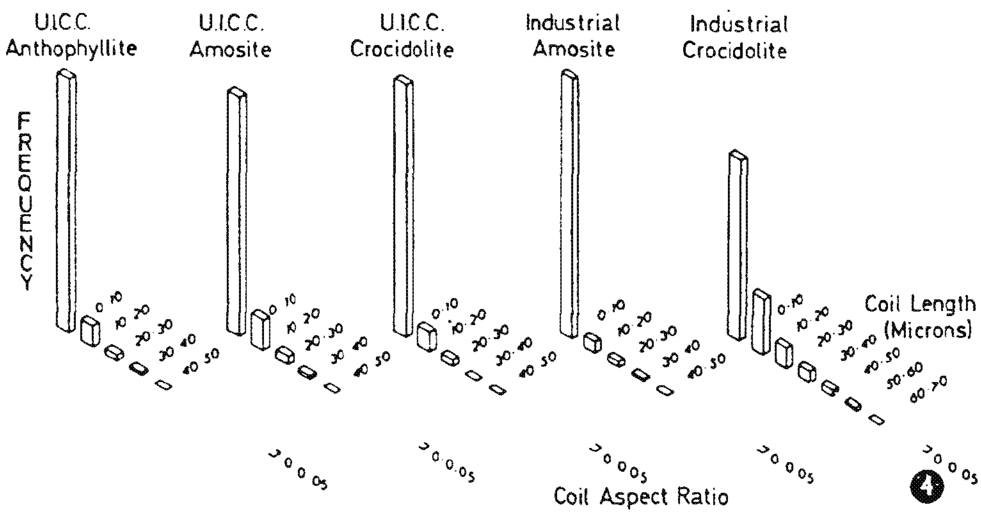

Fig. 4. Distributions of coil length and coil aspect ratio for amphiboles.

In contrast, a curly fibre in an airway can never exhibit an interception diameter as small as the actual fibre diameter. A minimum value is obtained if the axis of the fibre coil is parallel to the axis of the airway. Figs. 2 and 3 show that for a substantial proportion of long chrysotile fibres the coil diameters, and consequently the minimum interception diameters, are of the order of 20 microns or greater. Also, since curly fibres do not show a marked tendency to align themselves with respect to the axis of an airway even these minimum interception diameters would only be exhibited occasionally.

The gravitational settlement and inertial precipitation mechanisms are not entirely independent of the shape of a fibre. Curvature in a fibre increases the efficiency of these 2 mechanisms, for instance, introduction of curvature into a fibre reduces the distance the

The interception effect is important only in the narrow lung airways. These are short compared with the length of the respiratory tract. But they are of disproportionate importance in the present context since it is in these air ducts that normally the ciliary epithelium and mucus production terminate. Although curvature in a fibre might cause only a short reduction in the distance penetrated along one of these narrow airways it could mean a difference between landing on this escalator and travelling beyond it to reach a region whose geometrical complexity would make subsequent clearance of the fibre up the respiratory tract extremely difficult.

Animal Experiments

Recently the first results became available from an experiment in which groups of rats were exposed to dust clouds of the UICC reference fibres in equal mass concentrations of respirable dust as measured with the Casella Type 113A horizontal elutriator gravimetric sampler. The animals were killed 24 hours after the end of a 10 weeks' exposure. Approximately equal weights of dust were estimated in the lungs of the rats exposed to the 3 amphiboles. This was about 6 times the weights (approximately equal) estimated to be in the lungs exposed to the 2 chrysotiles. This ratio is about the same as that obtained between amosite and chrysotile in an earlier experiment when the materials used were not the UICC reference samples. (Wagner and Skidmore, 1965.)

Physical Experiments

The measured distributions of fibre length and of aerodynamic equivalent diameter are slightly coarser for the UICC chrysotile than for the UICC amphiboles (Timbrell, this Conference, p. 28). The percentage 'respirable' fractions determined using the Casella

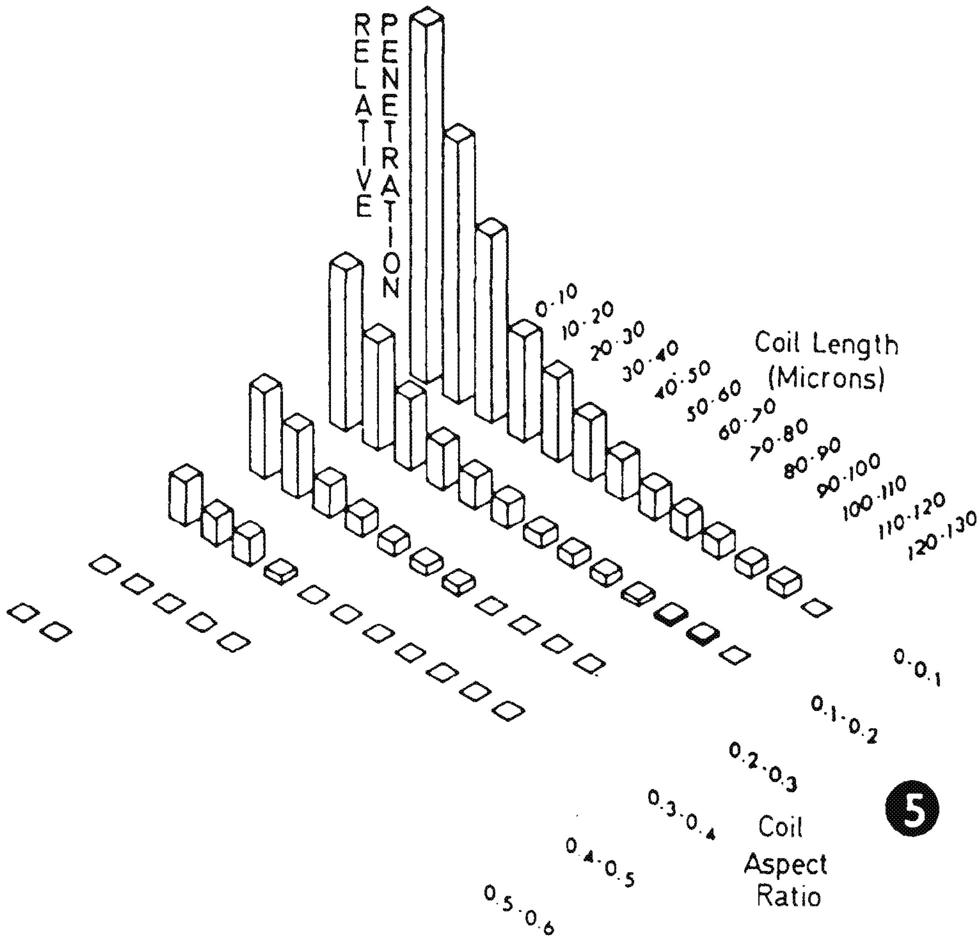

Fig. 5. Tube bundle experiment. Relative penetration of fibres in terms of coil length and coil aspect ratio.

Type 113A sampler are slightly greater for the amphiboles than the chrysotiles, although a reverse result has been obtained using the Unico 18 cyclone device. Overall, these measurements, which take little or no account of fibre shape, suggested that in animal experiments with the UICC reference samples more amosite than chrysotile would be deposited in rats' lungs in our experiment, but the difference should only be a few per cent.

There are a few possible explanations for the ratio of 6 actually obtained, including a suggested difference in the solubility rates of chrysotile and amphiboles in lung fluids. Clearly, the rates would have to be substantially different to effect this ratio of retained fibre after an exposure spread over only 10 weeks.

The different shape of the 2 types of fibre presents another possibility, and to investigate whether this is capable of producing a ratio large enough to be an explanation, experiments have been performed on the relative efficiency of penetration of curly and straight fibres through narrow tubes and hollow lung casts.

Fig. 5 shows the result obtained from an experiment in which a cloud of UICC Rhodesian chrysotile fibres was sucked through a bundle of 100 tubes 1 cm. long. The cloud contained enough straight fibres to give a result comparable with that which would be obtained from an amphibole. The tubes were 400 microns internal diameter and air velocities were arranged to simulate those in the narrow lung airways. Distributions of coil length and coil aspect ratio were constructed for the fibres presented to the tube bundle and for the fibres which penetrated. These were compared to construct the penetration diagram in Fig. 5. The results show decrease in penetration of the fibres with increase in coil length or coil aspect ratio and agree with the conclusions reached from consideration of the interception mechanism of particle deposition.

Using Fig. 5 and the distributions for UICC chrysotile and amosite in Figs. 2 and 4, computations have been made of the relative mass of chrysotile and amosite that would penetrate the bundle (and which in the analogy with the lung should travel beyond the ciliary epithelium) if equal masses of the two types were presented. This procedure was necessary because of difficulties, such as serious blockage of the tubes, in using a direct gravimetric method, if weighable samples were to be obtained.

The computations indicated that 5-6 times as much amosite as chrysotile should penetrate the tube bundle. This good agreement with the animal experiment depends to some extent on our favourable choice of tube dimensions, etc. in the physical study. The good agreement suggests, however, that fibre shape is an important factor in the efficiency of penetration through narrow ducts and must be considered a probable cause of the difference in the retention rates recorded for chrysotile and amphiboles in the animal experiment.

Hollow casts have been produced of pig and human lungs. The 'airways' can be cut at a required diameter and left open for the fibre cloud to be drawn through. The results have been more variable than in the studies on tube bundles, but even higher values have been obtained for the ratio of weights of amphibole and chrysotile.

Discussion

Long curly chrysotile fibres have been found in lungs, sometimes in numbers exceeding those observed for amphiboles. This however is not in conflict with the possibility that chrysotile fibres are generally less respirable than amphiboles, since chrysotile fibres readily divide into numerous flexible fibrils which are small in diameter compared with amphibole fibres. For instance, a chrysotile fibre of 1 micron diameter could yield 1,000 fine fibrils of the same length. An observation of large numbers of chrysotile fibres in lungs is thus not a good indication of a large mass being present. The experimental study of respirable asbestos fibres which was mentioned earlier suggested no similar subdividing of amphibole fibres, and comparison of fibre numbers is unlikely to be a good measure of relative mass of chrysotile and amphiboles in lungs.

An experiment reported elsewhere (Timbrell and Skidmore, 1968) using 'long-fibre' and 'short-fibre' clouds of amosite of approximately equal mass concentration of respirable fibres, indicated that the long fibres were the more fibrogenic. Other experiments (Vorwald, 1951) showed a similar relative importance of long fibres. The influence of fibre curvature on penetration is greatest for long fibres. These two factors working together could considerably reduce the fibrogenicity of inhaled chrysotile relative to that of an amphibole.

Some chrysotile clouds clearly visible to the naked eye have yielded respirable fractions as low as 5% when measured with the Casella sampler. These fractions are very much lower than those recorded for the chrysotile and amphibole UICC reference samples and some industrial dust clouds. There is therefore a need for more data of this type to determine whether there is another factor, quite apart from shape, which could make inhalation exposures from chrysotile clouds generally less than from the amphiboles.

Injection experiments do not simulate the deposition mechanisms which operate on inhaled particles, and such studies with fibres should be considered as examinations of their biological activity. This needs to be borne in mind when comparing the results of injection experiments with inhalation studies which are relevant to human exposure.

SUMMARY

Gravitational settlement and inertial impaction have the effect of limiting the diameters of asbestos fibres that can reach the pulmonary air spaces to less than about 3 microns.

Interception is important only in narrow airways and has 2 effects:

i. It concentrates long fibres in the narrow airways especially at bifurcations.

ii. It can cause a marked difference between the magnitude of retention of amphibole and chrysotile fibres.

REFERENCES

Timbrell, V. (1965): Ann. N.Y. Acad. Sci., **132**, 255-273.

Wagner, J. C. and Skidmore, J. W. (1965): Ann. N.Y. Acad. Sci., **132**, 77-86.

Timbrell, V. and Skidmore, J. W. (1968): *Proceedings of Dresden Conference*. In the press.

Vorwald, A. J. (1951): Arch. industr. Hyg., 3, 1-43.