Effect of Chemical Composition of Man-made Vitreous Fibers on the Rate of Dissolution in Vitro at Different pHs

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Measurements of rates of dissolution of typical insulation wool fibers (glasswool and basalt based stonewool) and an experimental fiber were made using a flow-through equipment. The liquids used were a modified Gamble’s solution, adjusted to pH 4.8 and 7.7 ± 0.2, respectively. The dissolution of SiO₂ and CaO was determined over periods of up to three months. The rate of dissolution of stonewool fibers was lower than that of glasswool fibers at pH 7.7, whereas the opposite was true at pH 4.8. The stonewool fibers dissolve congruently, but glasswool fibers tend to dissolve with leaching. The rates of dissolution of fibers of different compositions, including insulation wool (glasswool, basalt-based stonewool, slagwool) and experimental fibers were screened using a stationary set-up. Both the chemical composition and pH influenced the rates of dissolution. At pH 7.7 alumina was a determining component and at pH 4.8 the content of SiO₂ and CaO was determinant. One experimental fiber with a high content of alumina was an exception having a fairly high rate of dissolution both at pH 4.8 and 7.7. — Environ Health Perspect 102(Suppl 5):83-86 (1994)

Key words: in vitro, solubility, dissolution rate, MMVF, alumina, Gamble’s solution, pH, flow-through system, stationary system, glasswool, rockwool, basalt-based stonewool, slagwool, stonewool

Introduction

Concern for possible health effects of man-made vitreous fibers (MMVF) has generated a number of investigations in recent years. Fiber dimensions and time of residence in the lung appear to be among the important parameters for influencing the risk of disease. Residence time is dependent on the physical clearance of the fibers from the lung and on the rate of dissolution of the fibers.

The rate of dissolution of fibers may be assessed by in vitro measurements in which fibers are subjected to artificial, physiological solutions [Gamble’s solution, modified according to Scholze (1) or Kanapilly (2)], designed to resemble conditions in the lung fluids. These solutions all have a pH 7.4 to 7.8.

It is known that the pH in macrophages is more acidic than that of the lung fluid (3); and recent measurements of fiber durability, including in vivo measurements of the fiber dissolution in rat lungs (4–6), indicate that this difference in pH may account for different rates of dissolution. Moreover, when the fibers are sufficiently short, they may be engulfed by macrophages, which might explain the lower rate of dissolution observed for shorter glass fibers.

A number of in vitro investigations (1,7) have clearly demonstrated that the chemical composition of fibers has an influence on the rate of dissolution in artificial lung fluids at pH 7.4 to 7.8. Different pHs may also affect dissolution of some glass fibers (7).

Materials and Methods

Investigated Fibers

The fibers used for flow-through measurements were produced in normal full-scale production. The basalt-based stonewool fiber (MMVF 21) and the experimental high alumina fiber (HT-fiber) were produced without binder and oil, whereas the glasswool fiber (MMVF 11.2) contained some oil, which was removed by a cold ashing procedure. The fibers used for stationary measurements were mainly produced without binder and oil. The chemical composition of the fibers was determined by X-ray fluorescence spectroscopy (XRF, Philips 1404).

Dimensions of the Fiber Samples

The samples were sieved, and the fraction below 63 μm was used for the experiments. The length weighted diameter distribution was determined for each sample (8), by measuring 200 individual fibers by optical microscopy (×1000). The data were used together with density data for calculating the specific surface of the fiber samples.

Measurements of Rate of Dissolution: Flow-through Method

Five hundred milligrams of fibers were placed in polycarbonate filter holders (diameter, 40 mm). A 0.8-μm filter was placed on the inlet side (top) and a 0.2-μm filter on the outlet side (bottom) to avoid loss of fibers during the test. Both filters were cellulose nitrate. The flow-rate of the modified Gamble’s solution (Table 1) was kept at 100 to 110 ml/day by a peristaltic pump. The pH of the solution was maintained at 7.7 ± 0.2 by bubbling with N₂/CO₂ (95/5). For the solution at pH 4.8, add 3.7 ml/l concentrated hydrochloric acid.

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This paper was presented at the Workshop on Biopersistence of Respirable Synthetic Fibers and Minerals held 7–9 September 1992 in Lyon, France.

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Table 1. Composition of modified Gamble’s solution.

| Component   | g/l |
|-------------|-----|
| MgCl₂ · 6H₂O | 0.212 |
| NaCl        | 7.120 |
| CaCl₂ · 2H₂O | 0.029 |
| Na₂SO₄      | 0.079 |
| Na₂HPO₄     | 0.148 |
| NaHCO₃      | 1.950 |
| Na₂-tartrate · 2H₂O | 0.180 |
| Na₂citrate · 2H₂O   | 0.152 |
| 90% lactic acid   | 0.156 |
| Glycine     | 0.118 |
| Na-pyruvate | 0.172 |
| Formalin    | 1 ml |

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4.5, HCl (3.7 ml/l) was added. The entire set-up, including storage containers, was maintained at 37 ± 0.7°C. Effluent solution was collected once a week during 2 hr and analyzed for Si and Ca. Analyses were made on a Perkin-Elmer atomic absorption spectrophotometer (AAS).

Measurements of Rate of Dissolution—Stationary Set-up

Three hundred mg of fibers were placed in polyethylene bottles containing 500 ml of a modified Gamble's solution for one week. Once a day the pH was checked and if necessary adjusted by adding HCl. The bottles were kept at 37°C and shaken vigorously twice a day. Aliquots of the solution were taken out after one and four days and analyzed for Si by AAS. Some experiments were continued for up to 25 days.

Calculations

On the basis of the dissolution of SiO₂ (network dissolution), the specific thickness dissolved was calculated and the rate of dissolution established (nm/day). The

Table 2. Chemical composition of MMVF*: (wt.%) stationary solubility test.

| No.  | SiO₂  | Al₂O₃ | TiO₂ | FeO  | CaO  | MgO  | Na₂O | K₂O  | B₂O₃ | pH 7.7 | pH 4.5 |
|------|-------|-------|------|------|------|------|------|------|------|--------|--------|
| MMVF 21 | 46.0  | 13.0  | 2.8  | 6.3  | 16.8 | 9.2  | 2.8  | 1.2  | 0.0  | 3.0    | 6.5    |
| MMVF 11.2 | 61.9  | 4.2   | 0.1  | 0.0  | 8.3  | 0.9  | 15.5 | 0.8  | 5.9  | 9.3    | 0.9    |
| HT 3 | 38.7   | 31.9  | 1.7  | 6.8  | 15.3 | 2.0  | 0.3  | 0.7  | 0.0  | 6.6    | 63.7   |
| 4 | 48.2   | 5.4   | 0.1  | 0.6  | 27.1 | 15.1 | 1.0  | 0.2  | 0.0  | 9.1    | 17.9   |
| 5 | 49.1   | 0.6   | 0.1  | 0.0  | 29.3 | 16.4 | 0.1  | 0.0  | 0.0  | 45.5   | 32.5   |
| 6 | 46.9   | 15.1  | 1.7  | 5.3  | 16.6 | 9.8  | 2.5  | 1.0  | 0.0  | 2.3    |        |
| 7 | 46.7   | 13.3  | 2.1  | 6.8  | 16.4 | 7.8  | 2.6  | 1.2  | 0.0  | 2.2    |        |
| 8 | 50.0   | 6.4   | 0.5  | 3.0  | 24.6 | 11.3 | 0.7  | 1.4  | 0.0  | 7.7    | 10.2   |
| 9 | 58.6   | 0.7   | 0.1  | 0.1  | 15.2 | 3.3  | 15.2 | 0.7  | 4.0  | 185    |        |
| 10 | 48.1  | 9.7   | 1.7  | 6.0  | 15.9 | 11.5 | 1.4  | 1.5  | 0.0  | 2.0    |        |
| 11 | 58.8  | 0.8   | 0.2  | 3.6  | 0.8  | 27.2 | 5.4  | 0.4  | 0.0  | 71.2   | 2.1    |
| 12 | 48.4  | 8.7   | 1.6  | 5.4  | 13.0 | 10.3 | 10.4 | 1.4  | 0.0  | 3.7    | 3.4    |
| 13 | 52.8  | 4.0   | 12.0 | 0.8  | 1.6  | 10.0 | 20.6 | 0.5  | 0.0  | 3.2    | 1.0    |
| 14 | 42.6  | 13.8  | 0.7  | 0.5  | 33.9 | 5.1  | 0.7  | 1.5  | 0.0  | 5.2    | 78.0   |
| 15 | 50.3  | 6.4   | 0.8  | 7.2  | 12.5 | 18.5 | 0.3  | 0.4  | 0.0  | 5.3    |        |
| 16 | 61.9  | 4.0   | 0.2  | 0.2  | 8.0  | 3.1  | 14.8 | 0.8  | 3.8  | 12.4   |        |
| 17 | 52.9  | 3.6   | 0.1  | 0.8  | 7.2  | 2.7  | 16.1 | 1.3  | 4.4  | 9.9    |        |
| 18 | 62.2  | 3.0   | 0.1  | 0.6  | 7.6  | 3.4  | 17.4 | 1.2  | 2.3  | 15.4   |        |
| 19 | 41.9  | 8.6   | 0.3  | 0.4  | 36.2 | 9.2  | 0.7  | 0.8  | 0.0  | 11.9   | 58.7   |
| 20 | 60.1  | 0.8   | 0.2  | 4.0  | 12.5 | 19.9 | 0.1  | 0.4  | 0.0  | 31.7   |        |
| 21 | 57.7  | 0.7   | 0.2  | 0.6  | 37.6 | 1.3  | 0.1  | 0.5  | 0.0  | 43.4   | 8.2    |
| 22 | 62.2  | 0.1   | 0.1  | 0.1  | 20.8 | 15.6 | 0.1  | 0.1  | 0.0  | 44.5   | 0.5    |
| 23 | 53.8  | 43.8  | 0.1  | 0.1  | 0.1  | 0.3  | 0.1  | 0.0  | 0.9  | 1.7    |        |
| 24 | 51.8  | 45.8  | 0.1  | 0.1  | 0.1  | 0.2  | 0.3  | 0.1  | 0.0  | 1.4    | 1.3    |

*Numbers indicate the percentage of each fiber's weight attributable to each chemical.
Stationary Set-up

The dissolution rate (nm/day) for 24 chemically different MMVs, determined during a 1- to 4-day period, has been calculated based on SiO$_2$ dissolution (Table 2) and the results compared in relation to the chemical composition of the fibers.

Alumina was the only component to influence significantly the dissolution rate at pH 7.7. There is a reasonable correlation between the alumina content and dissolution rate over a wide range of alumina content (Figure 4).

Silicon and calcium both influence the dissolution rates at pH 4.5, but in opposite directions. Dissolution rates increase as the percentage of CaO increases (Figure 5), but they decrease with increasing SiO$_2$ content (Figure 6).

Discussion

Comparison of Measuring Methods

The advantage of the flow-through measurement is that conditions can be kept constant, and a constant dissolution rate can be established over a longer period. The disadvantages are that the method is time consuming (i.e., of long duration) and demands more resources (maintenance, analyses, calculations). The results are dependent on the flow rate, so that absolute values cannot be obtained. To avoid precipitation of carbonate in the flow system, the amount of Ca$^{2+}$ in the Gamble's solution was reduced compared with the solution used by Scholze et al. (1).

The stationary measurements are quite fast and simple to perform, enabling many samples to be investigated. The results, though, are not so reliable, as the dissolution of the fibers alters the composition and the pH of the solution during the experiment. Despite this, the dissolution rates for different fibers as determined by the dissolution during the first to fourth day, were in the same relative order as those obtained by the flow-through method (Table 3).

Measurements at Different pHs

It has been shown that fibers for which very different rates of dissolution were found in normal Gamble's solution at pH 7.4 to 7.8, cleared from animal lungs at almost the same rate (5). This may be due to the different environments present in the lung, and to the different mechanisms responsible for clearing and dissolving fibers from animal lungs.

Fiber length may determine the environment to which the fiber is exposed. Short fibers may be engulfed by the macrophages that have an intracellular pH 4.5-5, whereas the long fibers are subjected to the extracellular lung fluid with pH 7.4 to 7.8. It has been shown that only very short glass fibers were not dissolved.

calculations were based on the SiO$_2$ content in the fibers, the specific surface, and the amount of dissolved Si. For the flow-through measurements, new fiber diameter distributions were calculated weekly based on the determination of dissolved Si. Similar calculations were made on the basis of dissolved Ca.

Results

Flow-through Measurements

The nanometer dissolved (δD) has been calculated from the dissolution of CaO and SiO$_2$ and the results are given in Figures 1-3.

For the basalt based stonewool fiber (MMVF21), the cumulated dissolution whether based on Si or on Ca, is almost identical, indicating a congruent dissolution both at pH 4.8 and pH 7.7. However, the dissolution is faster at pH 4.8 than at pH 7.7 (Figure 1).

For the glasswool fiber (MMVF 11.2, Figure 2) the dissolution based on Ca is higher than that of Si at both pHs, indicating that the dissolution occurs partly through leaching. The thickness of the leached layer increases continuously, being approximately 0.3 μm after 2500 hr, at both pHs. However, the cumulative dissolution based on CaO, is five times higher at pH 7.7 than at pH 4.8. Based on SiO$_2$, the difference is even greater—some 25 times higher at pH 7.7 than at pH 4.8.

The experimental HT-fiber (Figure 3) dissolves quickly at pH 4.8, with a certain amount of leaching. The thickness of the leached layer continues to grow slowly during the test period. At pH 7.7 the dissolution rate is lower and no leaching is observed.

![Figure 4. Dissolution rates of 24 chemically different MMVs in nm/day, determined during a 1- to 4-day period using the stationary set-up at pH 7.7, and calculated from the measured SiO$_2$ dissolution. Specific dissolution rates are plotted against the molar percentage of Al$_2$O$_3$ in each MMVF.](image)

![Figure 5. Dissolution rates of 24 chemically different MMVs in nm/day, determined during a 1- to 4-day period using the stationary set-up at pH 4.5. The specific dissolution rates are plotted against the molar percentage of CaO in each MMVF.](image)

![Figure 6. Dissolution rates of 24 chemically different MMVs in nm/day, determined during a 1- to 4-day period using the stationary set-up at pH 4.5. The specific dissolution rates are plotted against the molar percentage of SiO$_2$ in each MMVF.](image)

| Fiber   | Flow-through test | Stationary test |
|---------|-------------------|-----------------|
|         | day 0-25          | day 1-4         |
|         | pH 4.8            | pH 4.8          |
|         | pH 7.7            | pH 7.7          |
| MMVF 21| 2.3               | 6.0             |
| MMVF 11.2| 3.0             | 8.2             |
| HT-3   | 15.0              | 63.7            |
|        | 2.9               | 7.6             |

*ln (nm/day).
after a certain time in the lungs, presumably because of their resistance to the acidic environment in the macrophages (4). The measurements carried out in the flow-through equipment showed that a fiber that dissolved readily at pH 7.7 did not necessarily dissolve fast at pH 4.8. The low alumina content of glass wool fibers favor dissolution at pH 7.7, whereas the high silicon content and the relatively low calcium content make this fiber less soluble at pH 4.8. Experimental HT-fibers do not fit this pattern. Despite their high alumina content, their rate of dissolution is quite high. In contrast, a typical basalt based stonewool fiber dissolves at a lower rate at pH 7.7 than at pH 4.8.

Experimental HT-fibers dissolve relatively fast at pH 4.8. This is to be expected from their low silica content and the relatively high calcium content. In in vivo studies it has been observed that the long fibers of the experimental HT-fiber are "broken" in the lungs of the rats (5). This could be because these fibers are very soluble in an acidic environment and the acidic "attack" of the macrophages are "cutting" the fibers into shorter fragments.

The marked effect of alumina content on dissolution rates at pH 7.7 is in agreement with previous findings (7), and patent applications within this field (9,10). Glass wool fibers (MMVF 11.2) when treated in the flow-through test at pH 4.8, had a low dissolution rate and showed signs of leaching of calcium, leaving an insoluble silica network (Figure 2).

Conclusion

Different types of MMVF fibers can have very different in vitro dissolution rates at pH 4.5 to 4.8 and pH 7.7 as shown for commercial glasswool (MMVF 11.2), basalt based stonewool (MMVF 21) and high-alumina (HT-3) experimental fiber. A high dissolution rate at pH 4.8 might increase the rate of fragmentation of fibers. Depending on their composition, fibers may dissolve congruently (basalt-based stonewool) or partly by leaching (glasswool and experimental HT fiber). To get a better correlation between fiber dissolution rates and biopersistence, the in vitro fiber dissolution rates at both pH 4.5 to 4.8 and 7.4 to 7.8 should be considered.

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