Scaling Bacterial Filtration Rates in Different Sized Porous Media

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ABSTRACT: Aquifer sediments contain a wide distribution of particle sizes, but only a single collector diameter (d) can be used in a filtration equation. To establish a method for selecting a characteristic d when media are composed of different sized particles, we measured bacterial retention in columns packed with either crushed quartz sand (separated into three different size ranges) or borosilicate glass beads. The best methods for choosing d were those that produced nearly constant collision efficiencies (ø). Characteristic diameters included: d0 (100% of all particles were smaller), d90 (90% of all particles were smaller), d4 (arithmetic mean), and d7 (geometric mean), where the diameters were calculated using number, area, and volume size distributions. Bacterial ø decreased in proportion to the distance traveled in the packed bed, and were scaled by the number of bacteria-sediment collisions using a dimensionless collision number (L). These comparisons indicated that characteristic diameters based on the smaller particles (d0 and d90, using number distributions, and d4 using a volume distribution) most accurately described bacterial transport in the different-sized porous media.

INTRODUCTION

The ability to predict bacterial transport is central to the study of a variety of subsurface processes, including microbial contamination of drinking water (Gerba 1985; Keswick 1984), and aquifer bioremediation (Wilson et al. 1986; Flathman et al. 1989). Although many aspects of bacterial transport are not completely understood, the use of clean-bed filtration theory (Yao et al. 1971; Rajagopalan and Tien 1976) has improved our understanding of factors that affect bacterial transport through ground-water aquifers (Harvey and Garabedian 1991).

Filtration models incorporate only a few soil and flow characteristics such as sediment size, porosity, and average fluid velocity to predict the collection frequency (ø) of particles such as bacteria with soil grains. Once particles collide with the soil grains, the probability of particles sticking to these grains is quantified in filtration models as the collection efficiency (ø). The collection efficiency therefore incorporates all chemical interactions between the particle and media, and any inaccuracy assumed in the calculation of ø.

Filtration theory has been verified in laboratory studies using uniform-sized, homogenous porous media. Although filtration theory has been used to describe the particle transport in soils and other media containing a distribution of particle sizes, there has been no methodological study performed to compare different methods of characterizing the single collector diameter for the filtration equation when the media consists of many different collector sizes. Researchers have therefore used a variety of different characteristic sizes, such as a weighted mean (McCaulou et al. 1995), median (Harvey et al. 1993; Harvey et al. 1995), or average grain size (Shonnard et al. 1994), or they have failed to scale the media used to specify the collector size (Horneberger et al. 1992).

The purpose of the present study was to examine the effect of different choices of the characteristic collector size on predicting bacterial transport in media containing a distribution of grain sizes. The retention of radio-labeled bacteria was measured separately in two crushed quartz sediments having different size distributions, and in a third sediment prepared as an equal mixture (by weight) of the two quartz media. Several characteristic collector sizes were used in the filtration equation to represent the size distributions of the media including: d4, d90, and d0, the sizes for which 10% and 90% of all particles in the distribution are smaller; d4, the geometric mean; and d90, the arithmetic mean. All characteristic sizes of media were determined from length (average diameter), area, and volume distributions measured using an image analysis system. Values of ø calculated from bacterial retention were assumed to be equal since the media differed only in size and not surface chemistry. Thus, methods to characterize the collector size that produced similar values of ø for all four different sized media were desired as a method for characterizing the grain size distributions in terms of a single collector diameter.

Comparisons of ø were made for both low and high ionic strength solutions because in moderate to low ionic strength groundwater solutions ø is not constant even when the bacteria are derived from a monoclonal population (Albinger et al. 1994). In low ionic strength solutions, the distribution of bacteria-collector affinities produces mean values of ø that decrease with increasing transport distance even in well cleaned, homogenous and uniform-sized media. It was hypothesized that by suspending cells in a high ionic strength solution that all cells would be completely destabilized. Therefore, bacterial transport in the different sized media was also examined using high ionic strength solutions (0.2 M CaCl2) in order to create conditions for constant ø values.

To compare the results from the different experiments on a similar basis, ø values were examined over the entire length of the packed bed based on a dimensionless collision number (L) used to scale the transport length by the rate of bacteria-sediment collisions. This collision number was derived by normalizing the rate particles entered the column by the rate bacteria collided with the column at a concentration equal to the influent concentration.

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The bacteria used for all experiments was *Pseudomonas fluorescens* strain P17 provided by C. P. Gerba (Department of Microbiology and Immunology, University of Arizona). The transport properties of P17 were established in previous studies (Kinoshita et al. 1993; Logan et al. 1993; Gross et al. 1993; Jewett et al. 1995). Cells were maintained by freezing 5 ml samples of P17 grown on glucose (0.25 g L⁻¹) in a morpholine-propanesulfonate (MOPS)/mineral salts medium, containing (per liter of distilled water) of the following: 4.62 g MOPS, 1.0 g NH₄Cl, 0.088 g CaCl₂-2H₂O, 0.05 g MgSO₄- 7H₂O, 0.17 g K₂HPO₄, and 0.087 mg FeCl₃-6H₂O. Protein cultures were thawned, transferred to 5 ml of tryptic soy broth (Sigma Chemical Co.), and incubated to stationary growth at room temperature on a test-tube rotator. A sample from the liquid culture (100 μL) was transferred to MOPS/mineral salts medium (10 ml) in a 250 ml Erlenmeyer flask, and incubated at room temperature on a shaker table (150 rpm). Cells were harvested during late log growth (A₅₁₀ = 1.00) and diluted into 100 ml of artificial ground water (see below) to a final concentration of 10⁷ cells/ml. Cells were radiolabeled by adding 40μL of 85 HLeucine (ICN, 79 Ci/mmol, 1 mCi/mL) to this suspension and incubating at room temperature for 8 h.

**Column Media**

Column packings used to simulate aquifer sediments were either 40 μm beryllium glass beads (Whetman) or quartz sand (Unimin Corp). The beads were cleaned by soaking in a 10% H₂SO₄ solution, agitating on a shaker table (150 rpm) for 3 h, and rinse with deionized water (Milli-Q, Millipore Corp.). Beads were dried overnight at 105°C and stored until use (Logan et al. 1993).

Different grain distributions of quartz media were prepared from stock quartz particles (Unimin Corp.) using a wet sedimentation technique (Litos and Olson 1993; Jewett 1995). Small particles were removed by flushing each quartz medium with tap water through the bottom of a 90 cm (length) x 7.5 cm (diameter) column at a constant flow that suspended all particles smaller than a chosen size based on the settling velocity. The overflow from the column was discarded. The desired size distribution was captured in the column effluent by fluidizing the bed at a higher flow rate, leaving larger particles in the column. Three different sizes of the quartz sand were separated in this manner, including: a large grain size (L), a small grain size (S₁), and a second small grain size distribution (S₂) used only in larger column experiments (see the following). A fourth medium was produced using a 50:50 mixture by weight of L and S₁.

Quartz media were cleaned by soaking in 12 N HCl for 24 h (with periodic agitation), rinsing with deionized water, and soaking at 80°C for 8 h. Once cooled, the quartz was rehydrated by boiling in deionized water for 4 h, dried at 105°C, and stored until use (Litos and Olson 1993).

Projected areas of sediment were measured by light microscopy (Olympus BH-2) on an Image analysis system (Came 2, Galac Inc.). The projected areas, A, were converted to equivalent diameters, dₑ, using A = πdₑ²/4. Particle diameters were converted to size distributions based on 10 μm increments (Fig. 1(a)). Size distributions were converted to area and volume distributions, assuming spherical particles (Figs. 1(b) and 1(c), respectively). These size distributions were used to calculate the four characteristic sizes of the sediment: S₁, A₀, dₑ, and dₙ₁ (Table 1).

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**FIG. 1. Particle Size Distributions for Small Quartz (S₁) and Large Quartz (L) Based on Following:**

(a) Number of Particles;

(b) Area of Particles; and

(c) Volume of Particles

**TABLE 1. Characteristic Sizes for Different Particle-Size Distributions**

<table>
<thead>
<tr>
<th>Column type</th>
<th>Column media (g)</th>
<th>Particle size range (μm)</th>
<th>Characteristic size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>—</td>
<td>Number</td>
<td>100</td>
</tr>
<tr>
<td>S₁</td>
<td>—</td>
<td>Area</td>
<td>118</td>
</tr>
<tr>
<td>S₂</td>
<td>—</td>
<td>Number</td>
<td>76</td>
</tr>
<tr>
<td>S₃</td>
<td>—</td>
<td>Area</td>
<td>118</td>
</tr>
<tr>
<td>S₄</td>
<td>—</td>
<td>Number</td>
<td>377</td>
</tr>
<tr>
<td>S₅</td>
<td>—</td>
<td>Area</td>
<td>377</td>
</tr>
<tr>
<td>L</td>
<td>—</td>
<td>Number</td>
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<tr>
<td>S₁</td>
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<td>Area</td>
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<tr>
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<td>—</td>
<td>Number</td>
<td>226</td>
</tr>
<tr>
<td>S₃</td>
<td>—</td>
<td>Area</td>
<td>226</td>
</tr>
</tbody>
</table>

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**Column Experiments**

Two types of column experiments were performed: mini-column experiments (3 cm ³ and 10 cm ³ syringes) run according to the Microbe and Radiolabel Kinetics (MARK) method (Gross et al. 1995) as modified by Ablinger et al. (1994), and large column experiments performed as described in Jewett (1995). Only the 10 cm ³ minicolumns packed with quartz media and minisulums (3 cm ³ syringes) filled
with glass beads were used to examine the variability in a over large ranges of collision numbers.

Bacteria were suspended in two different ionic strength solu-
tions, an artificial ground water (low ionic strength) and a
0.2 M CaCl₂ solution (high ionic strength). Artificial ground 
water (for the minicolumns consisted (per liter of deionized 
water) of the following: 0.069 g MgSO₄·7H₂O, 0.050 g 
NaHCO₃, 0.0145 g CaCl₂·2H₂O, 0.064 g Ca(NO₃)₂·4H₂O, and
0.002 g KCl. HCl (0.0N) was added to produce a final pH 
of 8 and ionic strength of 3.6 x 10⁻² M. The pH and ionic 
strength of the 0.2 M CaCl₂ solution were 6.8 and 6.0 x 10⁻² M,
respectively. Although the final pH and ionic strength of the 
artificial ground water for the large column experiments 
were the same as the artificial ground water used in the 
minicolumns (pH 8.1 and I = 4.4 x 10⁻² M, respectively), 
a slightly different ground water was used, consisting (per liter 
of deionized water) of the following: 0.006 g KNO₃, 0.138 g 
MgSO₄·7H₂O, 0.048 g CaSO₄·2H₂O, 0.019 g NaHCO₃, and 
0.047 g NaHCO₃.

Radiolabeled bacterial suspensions (50 ml) used in the 
large column experiments were filtered through a 0.2 µm 
syringe filter (Super Acrodisc, Gelman Scientific, Inc.) to re-
move unassimilated radiolabel. The filter was rinsed with 10 
ml of artificial ground water, re-pressed, and the cells pushed
off the filter using either the low or high ionic strength solu-
tions. This procedure was performed twice to obtain 100 ml 
of the final radiolabeled bacterial suspension. This procedure
was also used to resuspend the bacteria in the 0.2 M CaCl₂ 
solution for the minicolumn experiments.

The average projected area of cells was obtained using an 
epifluorescence microscope and the Image Analysis system.
Cells were stained by an acridine-orange procedure (Hobbit 
et al. 1977). Projected areas were converted to equivalent di-
ameter [A = (π/4)D²/2]. Equivalents cell diameters decreased 
during irradiation (1972) to 0.64 (1977) to 0.2 (1977), 0.2 (1972) to 0.14 (1977), n = 106) as a result of the syringe filtration step used to 
remove unassimilated radiolabel.

Minicolumn Experiments. The larger (10 cm) minicol-
umnas (inside diameter ID 1.3 cm) were filled with quartz 
media (small quartz, large quartz, or the quartz mixture) sup-
ported by a GfP filter (Whatman, 0.7 µm nominal pore size).
The smaller (3 cm) minicolumns (ID 0.8 cm) were filled with 
glass beads supported by a GfP filter (Whatman, 2.7 µm 
nominal pore size). Preweighed amounts of media (1.5 g glass 
beads, 6 g small quartz, 12 g large quartz, or 10 g quartz 
mixture) were added to the minicolumns by mixing in deion-
ized water, pouring the mixture into the column, and stirring 
the media with a Pasteur pipette to remove entrapped air. 
Columns were held on a vacuum manifold (Alltech) equipped 
with Luiselock connections.

To equilibrate the column media with groundwater solu-
tions (1 ml, 3 ml, 6 ml, 10 ml, 10 cm columns) of test solution (either artificial groundwater or 0.2 M CaCl₂) 
were pulled through the column and an approach velocity of 
0.9-1.4 x 10⁻² m/s selected by setting the vacuum pressure 
(3.5-8.0 cm H₂O, 0.16-0.35 m/s). The bacterial suspensions (in 
3 ml, 6 ml, 10 ml, 10 cm columns) was then pulled through the column, and the column was 
rinsed with either 4 ml (3 cm columns) or 12 ml (10 
cm columns) of the appropriate solution, to flush out unat-
tached cells.

The medium was removed from the column by cutting off 
the end of the column, and extruding it using the syringe 
plunger. Beginning at the top of the column, while the medium 
was extruded it was sliced in =1 mm (small quartz and glass 
beads), =6 mm (large quartz), or 2 mm (quartz mixture) in-
crements. Slicing intervals were selected to produce slices with 
similar collision numbers. Slices were transferred to pre-
weighed scintillation vials and weighed to determine the exact 
length of each slice (L).

Large Column Experiments. The experimental protocol 
for large column experiments was described in detail else-
where (Jewett 1995). Briefly, columns (diameter, 2.6 cm; 
length, 12.5 cm) were packed with small quartz (S₅) media to 
a depth of approximately 10.5 cm. Column inflow was con-
trolled in a downward direction at 4.5-8 x 10⁻⁵ m/s with 
pedestal infusion pumps (AVT Micro 210A, 3M Health Care).
A uniform water flow was established, and one pore volume 
(approximately 20 ml) of radiolabeled cells was pulled 
through the column, followed by three pore volumes of arti-
ficial ground water (low ionic strength experiments) or 0.2 M 
CaCl₂ (high ionic strength experiments). The column packing 
was removed, and the porous media was extruded in 1 cm 
sections, weighed, and transferred to scintillation vials as de-
scribed previously.

Cell Retention. Scintillation vials containing quartz or 
glass beads were filled with 10 ml of cocktail (Ecolite, ICN 
Biomedicals, Inc.), agitated for 18 h, and analyzed on a Beck-
man LS 3801 scintillation counter with quench correction.
The number of bacteria retained in each slice (N₅) was deter-
mimed from the mass of radiolabeled retained in the slice, corrected for unassimilated radiolabel as previously described (Gross et al. 1995). The number of bacteria added to the column (Nₛ) was estimated by radiolabel counts from total and filtered (0.2 µm 
polycarbonate filters, Poretics Corp.) bacterial suspension (2 
ml). The fraction of bacteria retained in each slice (R₅) was calculated as:

\[
R₅ = \frac{N₅}{Nₛ - \sum Nₗₜₜ}
\]  

(1)

where \( \sum Nₗₜₜ \) is mass of bacteria retained in previous 
sections. The fraction of bacteria that penetrated the column 
through the length of each slice (Cₛ/Cₛ) is therefore

\[
Cₛ/Cₛ = 1 - \sum Nₗₜₜ/Nₛ
\]  

(2)

where Cₛ is liquid phase concentration of bacteria at end of 
each slice; and Cₛ is influent concentration of bacteria.

THEORY

Filtration Equation

The fraction of bacteria remaining in the liquid phase after 
transport through a column of length (L) of porous media can 
be calculated from the one-dimensional filtration equation 
(Yao et al. 1971) as

\[
Cₛ/Cₛ = \exp(-\lambda L)
\]  

(3)

where \( Cₛ/Cₛ \) and \( Cₛ \) are concentration of particles entering and leav-
ning column; and \( \lambda \) is filter coefficient, calculated as

\[
\lambda = \frac{2}{d} \left( \frac{1 - \epsilon m}{\epsilon \eta L} \right)
\]  

(4)

where \( d \) = collector diameter; \( \epsilon \) = media porosity; and \( \eta \) = collector efficiency. Since \( Cₛ/Cₛ = (1 - R) \), the collision efficiency in each slice of column of thickness \( Lₛ \) can be cal-
culated by rearranging (3) in terms of \( R \) as

\[
\alphaₗ = \frac{2}{d} \left( \frac{1 - \epsilon m}{\epsilon \eta Lₛ} \right) \ln(1 - R)
\]  

(5)

The collector efficiency was calculated using the Rajagopalan

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\[ \eta = 4A_s^{1/2}N_s^{1/2} + A_s^{1/2}N_s^{1/2} + 0.00338A_s^{1/2}N_s^{1/2} \] (6)

where \( A_s, N_s, N_a, \) and \( N_o = \) dimensionless numbers that account for effects of neighboring particles, diffusion, Lennard-Jones, wall forces, interaction, and the number of particle collisions, respectively. These quantities were calculated by

\[ A_s = \frac{2(1 - \gamma^2)}{2 - 3\gamma} \times \frac{1}{1 - \gamma^2}, \quad N_s = \frac{d_s}{d_o}N_o = \frac{\text{mixfield}}{kT} \] (7-9)

\[ \gamma = (1 - e^{-\psi}), \quad H = \text{Hamaker constant (assumed here to be } 10^{-2} \text{m}), \quad \psi = \text{dynamic fluid viscosity} \times 10^{-4} \text{ Ns/m}^2; \quad d_s = \text{suspended particle diameter}; \quad U = \text{superficial fluid velocity}; \quad \gamma = \text{collector diameter}; \quad \zeta = \text{suspended particle density} \times 10^{-3} \text{ kg/m}^3; \quad \rho_f = \text{fluid density (971 kg/m}^3); \quad k = \text{Boltzmann's constant} \times 10^{13} \text{ kg} \cdot \text{m}^2 \cdot \text{s}^2 \cdot \text{K}^{-1}; \quad T = \text{fluid temperature (298 K).} \]

### Scaling Particle Removal Using Dimensionless Collision Number

Comparing bacterial filtration rates in media with different sized particles is difficult for several reasons. Even in two porous media that differ only in the collector size, removal rates of colloids varies in proportion to \( \eta/d \) and so removal rates will appear different when scaled by the distance traveled in the packed column. For the size range of typical soil particles, bacteria will collide more frequently with smaller than with larger soil particles, and will therefore be removed faster by smaller than larger soil grains. It was not known, however, if this generalization would be valid when media of different sizes were mixed together. Measuring bacterial filtration rates is further complicated by the fact that bacteria within a microparticulate population have a range of sticking coefficients (Allinger et al. 1994). The average \( \alpha \) of bacteria introduced into a column will therefore decrease with travel distance since the cells with higher \( \alpha \) are removed faster than cells with lower \( \alpha \). As a result, measured \( \alpha \) decreases with travel distance in the column. It is therefore not possible to directly compare bacterial removal from columns on the basis of a characteristic collector size in columns filled with different sized media without plotting travel distances on a common basis.

It is proposed here that bacterial removal rates measured in columns with different collector sizes can be directly compared on the basis of a dimensionless number, defined as the collision number \( \xi \), calculated as

\[ \xi = \frac{\text{rate particles collide in a column}}{\text{rate particles enter a column}} \] (12)

where both rates are evaluated on the common basis of the influent particle concentration. The rate particles enter a column of cross-sectional area \( A \) is \( \eta/d \). The rate particles collide is a column can either be calculated from a mass balance (Langan et al. 1995) or can be calculated by recognizing that the removal rate of particles is equal to the absolute value of the product of the collision rate and \( \alpha \). Particles are removed in the column at a rate \( dC/dt \), obtained from the chain rule as

\[ \frac{dC}{dt} = \frac{dC}{dV} \frac{dV}{dt} \] (13)

where \( dC/dt = \text{fluid velocity} \times U \). The instantaneous removal rate

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at the column entrance where \( C = C_0 \) is calculated by taking the derivative of (3), producing \( dC/dt = -\alpha C \). The collision rate is calculated as the absolute value of the product of the fluid velocity and the removal rate, \( dC/dt \), divided by \( \alpha \), or

\[ \frac{dC}{dt} = U - \frac{\alpha C}{\alpha} = -U \xi C \] (14)

Using these results in (12) for a column of volume \( V = AL \), the collision number is

\[ \xi = \frac{UACAL}{UCA} = \frac{A}{L}. \]

Thus, \( \xi \) can be seen to be a ratio of the column length to a characteristic travel distance (UA).

The utility of the collision number for scaling columns containing different sized media can be seen by comparing the fraction of bacteria penetrating two columns filled with 150 \( \mu \)m and 450 \( \mu \)m collectors. As shown in Fig. 2(a), assuming \( \alpha = 0.5, \quad U = 1.0 \times 10^{-3} \text{ m/s}, \quad d_s = 1 \mu \text{m}, \quad \eta = 0.37, \quad \) outer 5% of particles were removed within 3 cm in a column filled with 450 \( \mu \)m collectors, versus 30% in a column filled with 150 \( \mu \)m collectors. Because \( \alpha \) is constant, the difference in

![FIG. 2. Theoretical Transport of Particles through Columns with 150 \( \mu \)m Collectors Based on Filtration Model with All Particles Having \( \alpha = 0.5: \) (a) Fraction of Bacteria Penetrating Columns As Function of Transport Distance; (b) Fraction of Bacterial Penetrating Columns As Function of Collection Number; (c) Collision Efficiency (A) As Function of Collection Number (L) (Calculations Were Made Assuming \( U = 1 \times 10^{-3} \text{ m/s}, \quad \alpha = 0.37, \quad d_s = 1 \mu \text{m} \)).](image)
the penetration is due to a higher rate of particle-collector col-
lisions in the 150 µm collector diameter column than in the 450 µm collector diameter column. Utilization of the collision number to scale the column length results in identical pene-
tration for the two different collector sizes (Fig. 2(b)). Since α was assumed to be constant, values of α were also equivalent over the same number of collisions (Fig. 2(c)).

The collision number can also be used to scale removal rates in columns for particles with a distribution of collision effi-
ciencies. For example, the fraction of particles penetrating col-
lumns with either 150 µm or 450 µm collectors can be cal-
culated for a sample containing particles with two different collision efficiencies (50% of the influent particles have an α equal to 1 and 50% have an α equal to 0.01) (Fig. 3(a)). Mean values of α for each slice of the column were calculated using the filtration model (Fig. 3(b)). Mean values of α that would be measured in each slice decrease to 0.30 after 3 cm of trans-
port distance in the column with the 150 µm collectors, versus a decrease to 0.49 in the column with the 450 µm collectors. The increase in the rate at which α decreases is due to the increased collision rate with the 150 µm collectors. However, by comparing α on the basis of ξ instead of L, the results for both columns collapse onto the same line (Fig. 3(c)).

The magnitude of the collision number is also a useful pa-
rameter that indicates the number of collisions a nonattaching (α = 0) particle must undergo to travel through a column of length L. A collision number of unity, for example, indicates that a distance L = 1/α, is the distance non-attaching cells will collide once, on average, with column media.

RESULTS

Bacterial Transport in Low Ionic Strength Ground
Water

Bacterial transport in the low ionic strength (3.6 x 10^{-3} M) groundwater increased with collector size as predicted by theory (Fig. 4(a)). After 1 cm of transport distance approximately 90% of the bacteria penetrated columns with the large quartz collectors, versus 60% and 75% in column with the small quartz and the quartz mixture, respectively. When the filtration model (5) was used to calculate collision efficiencies (α) for each slice of the column, values of α decreased with increas-
ing transport distance (Fig. 4(b)). The change in α values for the different characteristic collector diameters is shown in Table 2. The dependence of α on transport distance was simi-
lar in the quartz mixture and the small quartz columns. Values

![Diagram](image-url)
Overall, values of $\alpha$ decreased an order of magnitude (3 to 0.2) after $\beta$.

### Bacterial Transport in High Ionic Strength Ground Water

To achieve more constant bacterial $\alpha$s, the column experiments were repeated using a high ionic strength ground water. As expected, the high ionic strength (6.0 $\times$ 10^{-3} M) solution decreased total bacterial penetration relative to the low ionic strength groundwater (Fig. 5a). Bacterial concentrations decreased by approximately 5% after 0.5 cm of transport distance in columns with the small quartz, 10% after 3.5 cm in columns with the large quartz, and 25% after 2 cm in columns with the quartz mixture. Collision efficiencies ($\gamma$) calculated in large and small quartz columns were constant, with $\gamma_s = 1.9$ ($\pm 0.2$ SE, Fig. 5b) when $\delta_s$ of the volume distribution was used as the characteristic collector diameter. Constant values of $\alpha_s$ were always observed in the columns with the small and large quartz media regardless of collector size (Table 3). In the columns with the quartz mixture, $\alpha_s$ decreased by a factor of 0.35. However, this overall decrease is much less than the overall decrease of a factor of 0.07 observed in the low ionic strength experiments.

Scaling column length by the number of collisions did not affect the overall trends in $\alpha_s$ (Fig. 6c). Values of $\alpha_s$ were still constant in the columns with the large and small quartz media, while $\alpha_s$ decreased only slightly in the columns filled with the quartz mixture. However, values for different column sizes were similar when compared on the basis of $\delta_s$ if a more appropriate choice of a characteristic collector size was used (see the following).

### Collision Efficiencies Measured over Large Range of Collision Numbers

To see whether trends observed in the micrololumns would scale over larger transport distances, $\alpha$'s were measured over a larger range of collision numbers ($\delta_s \leq 18$) using larger columns (instead of micrololumns) filled with the small quartz media and coconut charcoal + 10% small quartz glass beads. When $\alpha_s$ values were scaled by the collision number, $\alpha_s$'s for these different systems were nearly equal for $\delta_s \leq 18$, and indicated the same trend of a decreasing $\alpha$ with $\delta$ observed in the micrololumns with mixed quartz media at smaller collision numbers (Fig. 6d).

Overall, values of $\alpha_s$ decreased two orders of magnitude from 1.5 to 0.01 for bacteria suspended in the low ionic strength artificial groundwater (Fig. 6a). At lower collision numbers ($\delta_s < 1$ for quartz mixture), $\alpha_s$ decreased an order of magnitude from 1.5 to approximately 0.2. Similar order of magnitude reductions of $\alpha_s$ were observed in the glass bead micrololumns ($\alpha_s$ decreased from 0.4 to 0.03 for $0.2 < \delta_s < 5$) and the large columns filled with smaller quartz media ($\alpha_s$ decreased from 0.2 to 0.01 for $1 < \delta_s < 18$).
Higher values of α were produced by increasing the ionic strength, as expected from previous research (Gross and Logan 1995; Jeyewickrama et al. 1995). The high ionic strength solution also produced more nearly constant values of α over larger transport distances than observed in the low ionic strength experiments (Fig. 6b). For λ ranging from 1 to 10 in the large columns, α, for bacteria suspended in high ionic strength solution was constant at approximately 0.6. Collision numbers are not shown in Fig. 6b) for λ = 10 because the high ionic strength solution removed too many bacteria to permit accurate determination of α, at these largest travel distances. In the glass bead micromix, α, only slightly decreased from 0.8 to 0.5 (0.2 < λ < 3). In the quartz mixture micromix, the decrease in α was slightly larger, with α, decreasing from 2 to about 0.7 at low collision numbers (λ < 1) at high ionic strengths. However, this decrease was small compared to the order of magnitude increases observed in low ionic strength experiments for this media over the same range of collision numbers.

Choice of Characteristic Collector Size

Because of the large decrease in ξ, values with transport distance when bacteria were suspended in the low ionic strength solution, the characteristic collector size was determined from the experiments performed with the high ionic strength solution with nearly constant values of α for small values of ξ. The constant portion of the α versus ξ curves were used to visually compare the different methods of describing the distributions of collector size by a single value. Characterizing the sediments using d, or d, of the number distribution, or d, of the volume distribution resulted in similar values of α for the different media size distributions (Fig. 7).

Therefore, these three characteristic diameters were considered to be the best choice for representing different media size distributions.

ANALYSIS

The results comparing collision efficiencies of bacteria using different characteristic diameters to represent media with a distribution of grain sizes indicated that the most consistent values of α were obtained for methods that emphasized smaller particles in the size distribution. Porous media can therefore be characterized for use in a filtration equation using either d, or d, from a number distribution, or d, from a volume distribution. Since the media used in the present study had constant density, the volume distributions examined here would be equivalent to mass distributions produced by others to determine mean (McCauley et al. 1995) and median grain sizes (Harvey et al. 1995) of the porous media using sieving analyses. Values of α for d = d, were closer to (but in some cases still greater than) their theoretical maximum of unity suggesting that d, (based on a volume size distribution) is the best characteristic diameter for filtration calculations for heterogeneous media.

When larger characteristic media diameters were used in our experiments to characterize a grain size distribution, for example d, or d, of the volume distribution, we found that bacterial collision efficiencies for the columns with the quartz mixture were at least two times as large as collision efficiencies for the columns with the small or large quartz media (Table 3). Choosing too large a collector size results in predicting too few collisions between bacteria and the media, and underestimates the potential for bacterial removal by filtration. The three acceptable methods for defining a single characteristic collector size, of the 12 different methods examined, were therefore those that emphasized the role of the smaller particles in the porous media size distribution.

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Maximum collision efficiencies of \( x \) in the range of 2 to 3, calculated at small values of \( x \), were always larger than the theoretical maximum value of \( n = 1 \). Decreases in \( x \) were probably produced by removal of solute microcrystals near the column entrance, resulting in a lower overall \( x \) for bacteria that penetrate further into the column (Ahlgren et al. 1964). Calculated values of \( x > 1 \) may have been due to under prediction of \( x \) due to surface roughness (Harvey and Gascheidt 1955). For efficiencies determined by mean collision at a distance here due to adiabatic or polymeric coatings (Kunihata et al. 1963). Straining of bacteria can produce a \( x \) for \( d_{c} \geq 0.2 \mu m \) (Kunihata et al. 1963), but straining was not considered to be a factor since \( d_{c} \) was always less than 0.2 \( \mu m \) in our experiments. Collision efficiencies greater than 1 have been observed by others even for inorganic colloids (Logan et al. 1955). suggesting that collision frequencies are underestimated by the RT equation itself.

Other researchers have used more uniform sized collectors in experiments to study bacterial transport in porous media (Jeffers et al. 1961, Knutson et al. 1967, Martin et al. 1959). For highly uniform sediment distributions, the method of calculating a characteristic collector size is relatively unimportant since mean, average, and other characteristic diameters are essentially equal. In our experiments the choice of the characteristic collector size was therefore the most critical for the bidimensional distribution. The range in \( x \) was much larger for the quartz mixture with a broad size distribution than it was for the small and large quartz media which had narrower size distributions (Table 3).

Because measured bacterial collision efficiencies varied by orders of magnitude in low ionic strength experiments, the comparisons of characteristic collector sizes made on the basis of bacterial \( x \)'s different sized media were only possible when they traveled distances were non-dimensionalized using a collision number. This suggests that in future colonial and bacterial filtration studies \( x \) may be important to consider the number of collisions occurring in filtration tests to determine average \( x \). From our studies it appears that cumulums with the potential for least collision, or those colloid with lower collision numbers based on total column length, will have higher measured \( x \)'s than longer columns. If we extend these results to interpretations differences observed between laboratory studies (which typically have low collision numbers) and field tests (with high collision numbers) we would predict their lower \( x \) values in the laboratory than in the laboratory even for identical bacteria and sols. Harvey and Gascheidt (1963) calculated bacterial \( x \)'s in the range of 0.005 to 0.01 based on field tests using fluorescently stained indigenous bacterial and the Yao filtration equation (Yao et al. 1973) to predict their behavior. However, Rollins (1963), the use of more realistic (higher) cell densities and the RT model by Harvey and Gascheidt in their calculations would produce lower \( x \)'s that were lower in their study by a factor of \( 5.5 \). Such values were obtained by Bouwer and Rittmann to be close to lower limits of 0.001 observed in laboratory experiments. This observation of very low \( x \) in field tests is consistent with our results for experiments involving large collision numbers, suggesting that the low measured \( x \) could be the result of the large number of collisions required for bacteria to be transported over long distances. Additional research would be necessary, however to confirm this speculations.

In summary, our analysis indicates that \( d_{c} \) vs \( x \) by a number of different methods and the use of different distributions can adequately represent the distribution of collector sizes in \( d \)-selecting bacterial transport, and that bacterial transport distances should be scaled by the mean collision number \( x \). The use of a collision number approach in future studies may help explain variations in collision efficiency estimates under different laboratory and field conditions.

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APPENDIX. REFERENCES


