Comment on “A Method for Calculating Bacterial Deposition Coefficients Using the Fraction of Bacteria Recovered from Laboratory Columns”

SIR: Using an analytical solution to an advective-dispersive equation for bacterial transport, Bolster et al. (1) have correctly concluded that bacterial deposition coefficients in column experiments can be calculated based solely on the total influent and effluent bacterial concentrations. However, there are two important limitations of using their analytical and experimental approach. First, their analytical solution is not valid over the entire range of Peclet (Pe) numbers used in their analysis. Second, their method of measuring only the total recovery of bacteria in the effluent (rather than cells retained in the column) eliminates studying other important features of particle deposition within the column.

Bolster et al. (1) clearly illustrate how the deposition coefficient, $\kappa_1$, is related to the fractional recovery by

$$\kappa_1 = -\ln(fr) + \left(\frac{\ln(fr)^2}{Pe}\right)$$

where $fr = \frac{\text{fractional recovery from the column}}{\text{Pe} = \frac{vL}{D}}$, $v = \text{superficial fluid velocity}$, $L = \text{column length}$, and $D = \text{dispersion coefficient}$. Although Bolster et al. (1) are the first to show the derivation of eq 1, they neglected to note that Harvey and Garabedian (2) had already presented and applied this relationship to bacterial transport in porous media. They also did not cite another study (3) where it was calculated that a dispersion coefficient would have to be very large ($\approx 10^{-3} \text{ cm}^2 \text{s}^{-1}$) in order to significantly alter calculated bacterial deposition rates. A survey of dispersion coefficients indicated that there was little support for a dispersion coefficient of this magnitude in bacterial transport column experiments (3).

Bolster et al. (1) correctly concluded that dispersion can be neglected for $\text{Pe} > 10$; unfortunately, their solution (eq 6) of the governing transport equation is based on an equation in Parlange et al. (4) that is only valid for $\text{Pe} = 4$. As a result, the effect of Pe on deposition, shown in Figure 1 of Bolster et al. (1), is not valid for $\text{Pe} = 1$.

In most column studies, the Peclet number will be high. In such cases, the dispersion term (relative to advection) will only be important in regions with sharp concentration gradients, where the characteristic length scale is $L/\text{Pe}^{1/2}$. This scaling results from a balance of the dispersive terms against the transport due to advection and can be obtained by recognizing that dispersion has advanced a distance proportional to $(Dt)^{1/2}$ over a time $t$ (the dispersion velocity) relative to a fluid velocity $v$. In a column with a residence time $L/v$, the front is therefore spread over a distance $(DL/v)^{1/2} = L/\text{Pe}^{1/2}$. The fractional recovery of bacteria will accordingly be insensitive to dispersion for typical bacterial transport conditions since $L/\text{Pe}^{1/2} \ll L$ when $\text{Pe} \gg 1$.

The contribution of dispersion to overall transport at low Pe is more difficult to model when mechanical dispersion is much larger than molecular diffusion, and different results occur depending on the choice of boundary conditions used to solve the governing transport equation. Solutions used by both Bolster et al. (1) and others (3) overestimate the effect of dispersion on particle removal at low Pe. We believe, based on a review of the literature concerning the appropriate choice of boundary conditions used to solve such equations (4, 5) and recent work by Unice (6), that dispersion is unimportant for calculating the total mass of particles transported through the porous medium in column experiments. The boundary conditions chosen in Parlange et al. (4) require a mass balance at the column inlet and outlet but therefore fail to preserve the normal distribution of velocities (mechanical dispersion) that produces longitudinal dispersion in porous media. Mass and dispersion can both be preserved if it is assumed that the column is infinite or that the column ends do not affect dispersion. The infinite column assumption is reasonable as long as mechanical dispersion is large compared to molecular diffusion. An analysis based on a pulse input into an infinite column (see below) and that of Bolster et al. (1) indicates that dispersion can be neglected in calculating total bacterial recovery.

For an instantaneous pulse injection with an irreversible first-order reaction (rate constant, $k_c$), the one-dimensional transport equation is

$$\frac{\partial C}{\partial t} + \frac{\partial C_x}{\partial x} = D \frac{\partial^2 C}{\partial x^2} - k_c C$$

where $C$ is the concentration of suspended bacteria. This is the same equation as in Bolster et al. (1) except that desorption is neglected here. This equation can be solved with the initial condition

$$C(x,0) = \frac{M}{A \theta \delta(x)}$$

and the boundary conditions $C(\pm \infty, t) = 0$. The initial condition is written for a pulse injection of mass $M$, where $A = \text{cross-sectional area}$, $\theta = \text{porosity}$, and $\delta(x)$ is the dirac delta function. Using the transformation $C = C^* e^{k_c t}$, eq 2 becomes

$$\frac{\partial C^*}{\partial t} + \frac{\partial C^*_x}{\partial x} = D \frac{\partial^2 C^*}{\partial x^2}$$

The solution to eq 4 with the above boundary conditions relative to a moving front is

$$C^*(x,t) = \frac{M}{A \theta \sqrt{4\pi Dt}} \exp\left(-\frac{(x-vt)^2}{4Dt}\right)$$

where the mass of bacteria is decayed over time at a rate dependent on the deposition coefficient, $k_c$, according to

$$M = M_0 e^{-k_c t}$$

for an initial mass of bacteria, $M_0$. The difference between our approach and that by Bolster et al. (1) is in our assumptions of how the column inlet and outlet affect dispersion. In the above approach, it is assumed that the ends of the column do not alter dispersion and, therefore, that the pulse moves in the same manner in the column as it would in an infinitely long (unbounded) system. Application of eqs 5–6 for bacterial transport in a column leads to the conclusion that the mass recovered in the column (i.e. that reacted away) after the passage of the pulse through the column does not depend on the dispersion coefficient for a first-order reaction. By superposition using a series of pulse injections, the same conclusion would be reached for an injection over a longer period of time.
Unfortunately, because $D$ and $\kappa$ are a function of velocity, and because $D$ can increase with distance (7), it is unlikely that the small differences depicted in Figure 2 of Bolster et al. (1) could ever properly be experimentally tested and this issue resolved. Using either the analysis above or that in Bolster et al. (1), it is concluded that dispersion of the magnitude measured in laboratory column experiments would not affect the total mass of deposited cells in column studies. Filtration models that neglect dispersion (8, 9) can therefore be applied to particle retention studies in the laboratory.

The test described by Bolster et al. (1) is essentially the same approach used in the microbe and radiolabel kinesis or MARK method (10) except that in the MARK test the fraction of retained cells, not those in the effluent, are typically measured. The MARK test can be used as a one-step procedure to measure overall bacterial deposition coefficients (10), or, by extruding and slicing up the column, deposition rates can be measured as a function of transport distance (11, 12). The experimental method described by Bolster et al. (1) of calculating deposition coefficients based on total cell recovery in the effluent will work. However, by not directly examining particle deposition within a column, their approach neglects useful data for examining important deposition mechanisms such as blocking and filter ripening (13, 14). Intra-column experiments have shown that the collision efficiency $\alpha$ is not always constant, even over a length scale of one or a few centimeters (11, 12, 15). Such tests have therefore been useful to probe the roles of soil (16) and bacterial population (11, 15) heterogeneities on bacterial transport in porous media.

Finally, we disagree with the assertions of Bolster et al. (1) made with regard to the MARK procedure, that “the dissection of a column and enumeration of the deposited bacteria is relatively time-consuming and is not a practical measurement to consider on large numbers of cores”. Enumeration of deposited bacteria is neither time-consuming nor impractical. First, the MARK test can be based on a single slice, and analysis of one slice takes no more time than analysis of an effluent sample. Second, radiolabeling bacteria may save time when analyzing a large number of samples. Radiolabeled cell concentrations can be rapidly measured using a scintillation counter, rather than through more time-consuming plating or microscope-based counting techniques—which are not accurate if the column effluent contains large numbers of indigenous microorganisms. Third, by conducting MARK tests using multiple 1- or 2-cm-long minicolumns held in a vacuum box, a better statistical analysis of retention coefficients can be performed on a large number of soil samples versus that possible in the same amount of time using larger pumped columns. Fourth, an advantage of measuring retained cells in a MARK test is the ability to more accurately measure low bacterial concentrations retained in a column when bacterial recovery in the effluent is high. Bolster et al. (1) suggested their method be used for measuring deposition coefficients when bacterial recovery in the effluent is low. Although the MARK test was initially developed to detect high effluent recoveries, it has been shown to produce reliable results when effluent recoveries are low (12).

In conclusion, we thank Bolster et al. (1) for emphasizing that bacterial deposition in porous media columns is not affected by dispersion at high Penumber. However, it must also be recognized that longitudinal dispersion should not affect bacterial deposition at any Pe in unbounded systems (i.e., in the field). Although measuring total retention or recovery of cells in an effluent does permit rapid calculation of an overall deposition coefficient, by measuring particle deposition as a function of column length in a MARK test it is possible to gain additional insight into other mechanisms that may affect colloid transport in porous media.

**Literature Cited**


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