Reply

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We thank *Ginn* [this issue] for his interest in and close inspection of our paper. His comments raise some points regarding the paper by *Rehmann et al*. [1999] that we wish to clarify.

Ginn first comments on the finding that our mean model could predict virus breakthrough preceding that of a conservative tracer. Ginn states that "size exclusion is the exclusion of suspended colloids or particles from lower-velocity regions of pore space due to the size of the suspended material particle." The phenomenon that Ginn defines as size exclusion, generally referred to as hydrodynamic chromatography [*Small*, 1974], is not referred to anywhere in our work. We point out that the term "size exclusion," as we have used the term, has been used extensively in the colloid transport literature to indicate as defined by *Rehmann et al*. [1999, p. 1987] that "colloids, unable to fit into the smaller pores, are limited to transport in larger ones" [e.g., *Kretzschmar et al*., 1997; *McKay et al*., 1993; *Harvey*, 1991, 1997]. *Bales et al*. [1989] have used the term "volume exclusion" to describe this phenomenon. The primary mechanisms that can result in virus breakthrough preceding that of a conservative tracer are: (1) what we define as [volume] size exclusion (exclusion of colloids from smaller pores due to their inability to fit into them); (2) preferential flow through high-conductivity regions; and (3) what Ginn defines as size exclusion or hydrodynamic chromatography (exclusion of colloids from the lower-velocity regions of a pore throat due to their size). We agree with Ginn that these processes and the extent to which they affect colloid transport in porous media are poorly understood, and as stated previously, our work does not include the phenomenon defined by Ginn as size exclusion. It was our intention to investigate the extent to which the incorporation of heterogeneous aquifer parameters (i.e., hydraulic conductivity, pore water velocity, porosity, colloid filtration, etc.) affect virus transport behavior such as early virus breakthrough.

Ginn further states that equation (1a) of *Rehmann et al*. [1999] is free of a porosity transport operator. However, the development of equation (1a) results in the presence of porosity in two key terms: first, the filtration term, and second, the detachment term. Porosity has been perturbed in both of these parameter groupings in our analysis as well as in the local attachment equation (1b), both of which affect the resulting mean equation (30a) for free virus transport; we speculate that it is the perturbation of porosity in the filtration term that, in fact, can result in the early breakthrough behavior. Although colloid filtration appears as a loss term in the local-scale equation for free virus transport, the complexity of the mean result (30a) makes it difficult to discern the implications of the heterogeneous filtration term. Until our model is validated, which we explicitly stated as an important next step in this work, we cannot state in quantitative detail how the model will compare to Monte Carlo or other relevant simulation results.

Ginn also notes that if the ln K variance is taken to zero in the mean equation, the effective velocity of the viruses (v_e) reduces to the mean pore water velocity and the remaining terms in such an equation are incapable of generating "size exclusion-type effects." We point out that not only is it obvious that the mean equation (30a) reduces to the local equation (1a) when the heterogeneous terms are taken to zero (all terms in (30a) that are understuck disappear), there would be an error in the mathematics if it did not. One of the main points of the paper is that terms appearing in the derived mean equation do not appear in the local equation and are due to the effects of aquifer heterogeneity; the purpose of the simulations was to evaluate the magnitude of these terms. Regarding the form of the local scale equation, we did not claim that the local-scale equation was capable of simulating the hydrodynamic chromatographic effect.

Finally, Ginn disagrees with our argument that the use of a high ln K variance value σ_f^2) could potentially lead to faster virus breakthrough via what we define as the size exclusion effect. Ginn states that it is preferential flow through connected pores, unrelated to the ln K variance, that affects virus breakthrough. We argue that both preferential flow and volume size exclusion effects are influenced by the ln K variance value. As stated by *Rehmann et al*. [1999], the high ln K variance value implies that more of the aquifer is characterized by the tails of the ln K distribution. The "high ln K tail" characterizes very conductive lenses through which viruses would flow preferentially due to their inability to fit into the smaller pores of the less conductive "low ln K tail" aquifer material. Therefore we are not suggesting in this analysis that the connectivity of the lenses is affected by the ln K variance value leading to preferential flow but that the ln K variance value affects the fraction of aquifer material accessible to the viruses. "Preferential flow" has been used previously to describe a favored flow path in a heterogeneous aquifer which is composed of coarser sand or gravel [*Harvey*, 1997] and therefore a greater volume of highly conductive lenses. This situation increases the preferential flow paths available to viruses, and the volume size exclusion effect is also more pronounced as there is a wider pore size distribution present.

In summary, we thank Ginn for giving us the opportunity to

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clarify some points in our work. It is likely that faster transport for viruses and other colloids through granular aquifer material relative to conservative tracer involves several mechanisms, and more mechanistic studies are needed to determine the relative contributions of each. Judging from results of flow-through column studies involving structured heterogeneities (zones of different hydraulic conductivities [e.g., *Fontes et al*., 1991]), physical heterogeneities in granular aquifers can be an important determinant of faster microbial breakthrough through saturated granular media relative to conservative tracers. We believe that predictions of enhanced virus transport using a model that accounts for the variations in hydraulic conductivity is quite reasonable.

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