

Molecular Simulation of Alkylsilane Stationary Phases in Liquid Chromatography

“Shape-selective” polymeric stationary phases are routinely employed over the more common monomeric stationary phases in reversed-phase liquid chromatography (LC) to improve the separation of geometric isomers of constrained solutes, such as polycyclic aromatic hydrocarbons, carotenoids, steroids, and polychlorinated biphenyls. Critical to describing such shape-selectivity processes in LC is the elucidation of the molecular-level structural features of the alkylsilane stationary phase that promote such separations. The evaluation of these potential molecular recognition sites within an alkyl-modified surface can be achieved through the use of computational tools, such as molecular dynamic simulation and surface topography techniques. Results from these modeling investigations are intended to support the elucidation of shape-selective retentive processes.

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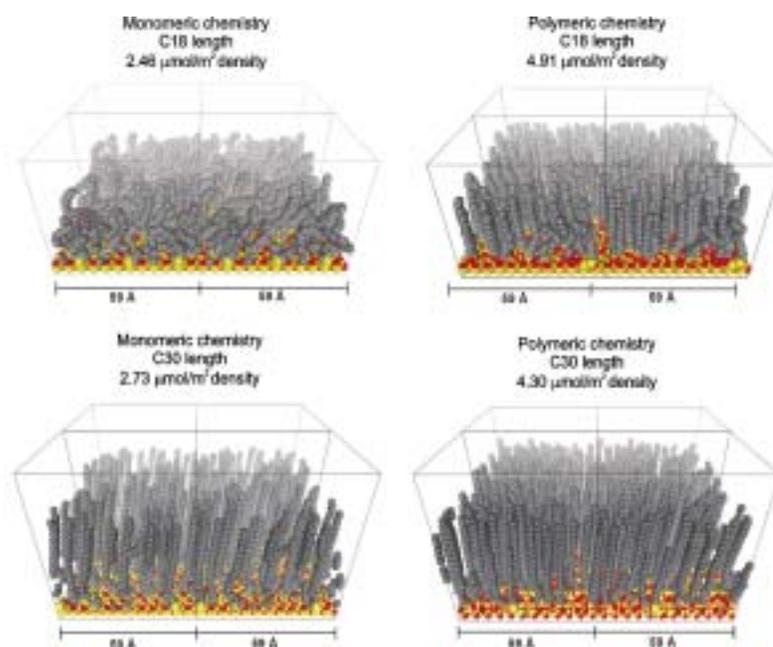
NIST researchers have investigated the molecular dynamics (MD) of chromatographic models that represent both monomeric and polymeric stationary phases with alkylsilane surface coverages and bonding chemistries typical of actual materials in an effort to elucidate the molecular-level structural features that control shape-selective separations. The structural characterization of these models is consistent with previous experimental observations of alkyl chain order and disorder. Highly ordered morphological features were characterized (identified) for simulated chromatographic models that represent materials with enhanced shape recognition capability. Deep cavities within the alkyl chains were identified for models representing shape-selective stationary phases. These results provide a more robust physical representation of alkyl-modified surfaces that supports the elucidation of retentive processes, as well as illustrating the potential for such computational techniques to predict the molecular recognition capabilities of novel analyte-specific sorbents.

MD simulations of C₈-, C₁₈-, and C₃₀-modified silicas have been carried out to study changes in stationary phase architecture that may result from variations in chain length, bonding density, synthetic approach, and temperature. Surfaces were modeled using a quartz substrate with vicinal –OH groups (9.8 μmol/m²), and alkyldimethylsiloxane or alkyldisilanol siloxane groups were linked via siloxane bonds. Surface densities ranged from 1.6 μmol/m² to 5.9 μmol/m² for C₈, C₁₈, and C₃₀ ligands, and some models were constructed of three oligomer units to approximate bonding in polymeric phases.

Results from these models highlighted several trends in molecular structure. The thickness of the phases increased with increased bonding density as individual chains were more constrained by neighbors. Correspondingly, the *gauche* fraction also decreased with increased density. At the same bonding density, longer chain length phases were more ordered than shorter chain length phases. Finally, increased order was observed at reduced temperature. The resultant model snapshots shown below exemplified the aggregate structural features observed for chromatography phase models of varying bonding chemistry, density, and length. Chain extension and increased *trans* conformations are observed with models of polymeric C₁₈ phases. C₃₀ stationary phase models exhibit significantly increased *trans* conformations, even with lower surface densities. Figure 1 shows snapshots from molecular dynamic simulations of various monomeric and

polymeric C₁₈ and C₃₀ stationary phases.

Analytical shape computation techniques were applied for the detection of cavities and the calculation of molecular surface properties of isolated cavity features and other ordered formations within these resultant alkyl stationary phase simulation models. Deep cavities 0.8 nm to 1 nm wide (8 Å to 10 Å) within the alkyl chains were identi-



fied for C_{18} polymeric models representing shape-selective stationary phases (Figure 2). Similar-structure cavities with significant alkyl chain ordered regions (> 1.1 nm or 11 \AA) were isolated from two independent C_{18} models (differing in bonding chemistry, density, and temperature) that represent highly shape-selective materials. The size and depth of these ordered regions increased (up to 2.8 nm or 28 \AA) for the extended-length C_{30} alkyl phase models. These results provide a more robust physical representation of alkyl-modified surfaces that supports the elucidation of retentive processes.

Impact: The models that have resulted from this study clearly indicate the extent of molecular order within alkyl-modified surfaces and are consistent with spectroscopic studies (e.g., Raman, ^{13}C NMR, and infrared spectroscopy). The results provide a compelling molecular-level vision of alkyl-modified surfaces that will guide future development of materials for chromatographic and biotechnological applications.

Future Plans: It is our continuing goal to investigate such molecular-level interactions by simulating constrained-shape solute interactions with fully solvated (i.e., water-acetonitrile mixtures) reversed-phase LC models to represent a range of shape-selective chromatographic behavior. In addition, the docking of solutes with various shapes and molecular dimensions from the liquid phase to the alkyl stationary phase will be employed to determine the effectiveness of these morphological features in the shape recognition process.

Publications:

K. A. Lippa, L.C. Sander, R.D. Mountain, **Molecular Dynamics Simulations of Alkylsilane Stationary-Phase Order and Disorder. 1. Effects of Surface Coverage and Bonding Chemistry**, *Anal. Chem.*, 77 (24), 7852 - 7861, 2005.

K.A. Lippa, L.C. Sander, R.D. Mountain, **Molecular Dynamics Simulations of Alkylsilane Stationary-Phase Order and Disorder. 2. Effects of Temperature and Chain Length**, *Anal. Chem.*, 77 (24), 7862 -7871, 2005.

K.A. Lippa, L.C. Sander, **Cavity Formations within Alkyl-Modified Surfaces via Molecular Dynamic Simulations**, *J. Chromatography A*, 1128 (2006) 79-89, 2006.

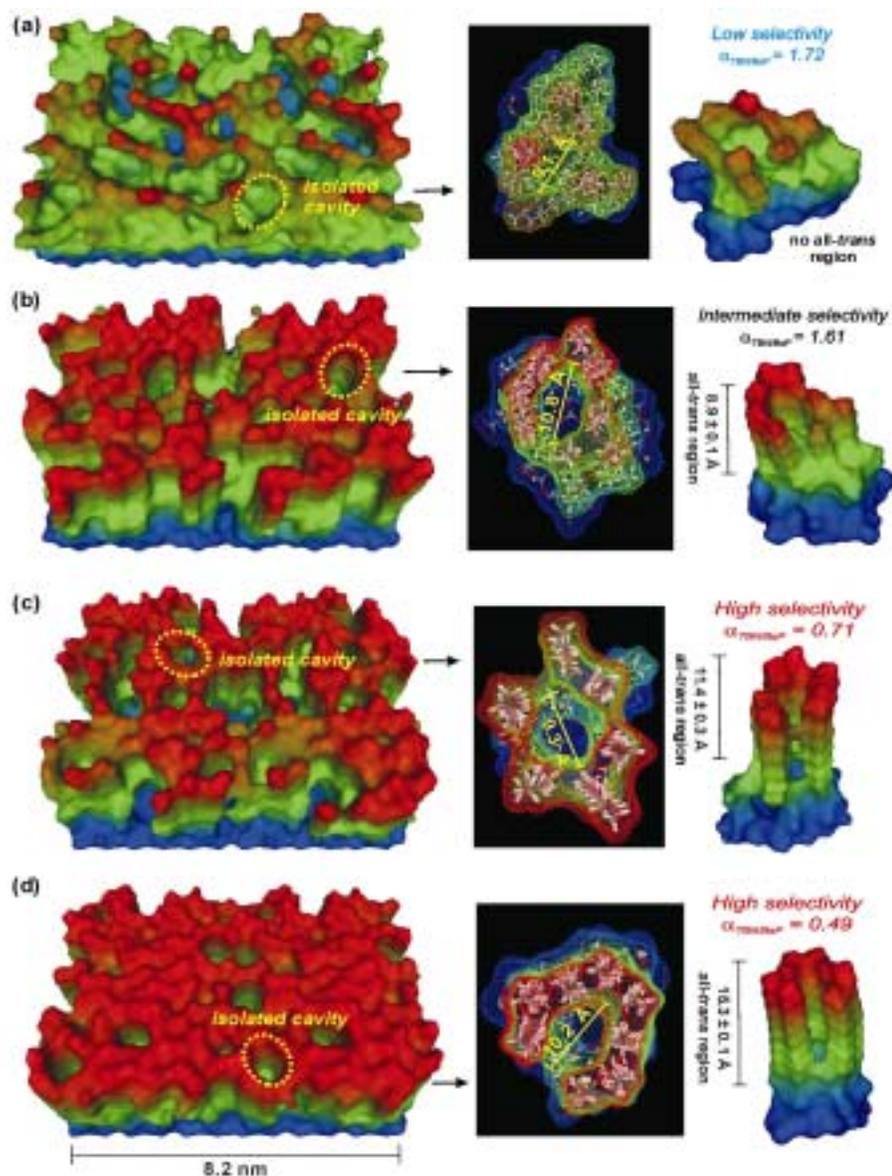


Figure 2 shows molecular surfaces generated for molecular dynamic simulation snapshots of (a) C_{18} monomeric model at $3.28 \mu\text{mol/m}^2$ surface coverage representing an actual RPLC phase with low shape selectivity for tetra-benzonaphthalene (TBN) and benzo[a]pyrene (BaP) ($\alpha_{\text{TBN/BaP}} = 1.72$) and three C_{18} polymeric models at (b) $3.89 \mu\text{mol/m}^2$, (c) $4.91 \mu\text{mol/m}^2$ and (d) $5.94 \mu\text{mol/m}^2$ surface coverages also representing actual phases with intermediate to high shape selectivity ($\alpha_{\text{TBN/BaP}}$ from 1.61 to 0.49). Surfaces are color-coded according to the height along the z-axis.