AFM/Bacteria: A partial bibliography

The categories are very fuzzy since many papers contain some combination of force measurements, imaging, and adhesion measurements. The section on adhesion measurements is especially incomplete since there are a large number of papers using AFM to study bacterial adhesion and we are mostly interested in elasticity measurements for now. Otherwise, I think these papers and their references represent a decent cross section of the AFM work done so far on bacteria.

Reviews:

Dufrene (2002) *Atomic Force Microscopy, a Powerful Tool in Microbiology*. Journal of Bacteriology **184**:5205

Review of AFM in bacteriology.

Force Measurements of Bacteria (and yeast) with AFM:

Arnoldi *et al.* (1998) *Elastic properties of the cell wall of* Magnetospirillum gryphiswaldense *investigated by atomic force microscopy*. Applied Physics A **66**:S613

See (Arnoldi, 2000) for essentially the same results augmented with better procedure (bacteria were not frozen and thawed before force measurements) and with theory of indentation (theory also described in (Boulbitch, 2000)).

Arnoldi *et al.* (2000) *Bacterial turgor pressure can be measured by atomic force microscopy*. Physical Review E **62**:1032

Used theory also described in (Boulbitch, 2000) to measure bacterial turgor pressure. Used DETA-coated glass to immobilize bacteria, but simple incubation was not sufficient: they also had to sandwich the sample between another glass slide to get good adhesion.

Beech *et al.* (2002) *The use of atomic force microscopy for studying interactions of bacterial biofilms with surfaces*. Colloids and Surfaces B **23**:231

Discussed imaging as well as adhesion and elasticity measurements with AFM. They focus on biofilm forming bacteria on metals.

Boulbitch (2000) *Deformation of the envelope of a spherical Gram-negative bacterium during the atomic force microscopic measurements*. J. Electron Micros. (**49**)**3**:459

Theoretical paper discussing indentation. Find that indentation is linear and can be described by a spring constant that is proportional to the turgor pressure.

Touhami *et al.* (2003) *Nanoscale Mapping of the Elasticity of Microbial Cells by Atomic Force Microscopy.* Langmuir **19**:4539

Imaged *S. cerevisiae* immobilized in porous membrane showing a bud scar, collected force curves, and used Hertz model to calculate a Young's modulus ~6 MPa for the bud scar and ~0.6 MPa for the mother cell surface.

van der Mei *et al.* (2001) *Measurements of Softness of Microbial Cell Surfaces*. Methods

Enzymology. **337**:270

Discuss relationship between AFM force curves and electrophoretic mobility through envelope.

Velegol and Logan (2002) *Contributions of Bacterial Surface Polymers, Electrostatics, and Cell Elasticity to the Shape of AFM Force Curves*. Langmuir **18**:5256

Try to analyze shape of nonlinear portion of force curves and conclude that cell envelope elasticity is responsible but this interpretation is not really consistent with their data since their control curves on glass show the same nonlinearity. Used Polyethyleneimmine-coated glass to immobilize bacteria.

Yao *et al.* (1999) *Thickness and Elasticity of Gram-Negative Murein Sacculi Measured by Atomic Force Microscopy*. Journal of Bacteriology **181**:6865

Measured the elasticity of sacculi from *E. coli* and *P. aeruginosa* suspended over a groove etched in a silicon surface in air.

Imaging Bacteria with AFM:

Doktycz *et al.* (2003) *AFM imaging of bacteria in liquid media immobilized on gelatin coated mica surfaces.* Ultramicroscopy **97**:209

Coated mica with poly-L-lysine of different molecular weights and gelatin from different companies and compared the adhesion of *E. coli* and *S. aureus* to the surfaces. Out of polylysines, 300 Kd worked best, but gelatin worked even better. Bacteria allowed to adsorb directly from liquid minimal media adsorbed consistently more reliably than bacteria grown on a plate and resuspended in water. Complex media (those with multiple carbon sources) were found to interfere with immobilization in all cases.

Kasas *et al.* (1994) *Observation of the action of penicillin on* Bacillus subtilis *using atomic force microscopy: Technique and the preparation of bacteria.* Surface and Interface Analysis **21**:400

Made observations in air. Imaged bacteria before and after treatment with antibiotics.

Kolari *et al.* (2002) *Firm but Slippery Attachment of* Deinococcus geothermalis. Journal of Bacteriology **184**:2473

Imaged *Deinococcus geothermalis* biofilms on glass and steel. Bacteria on the surface were repositioned laterally significantly more easily than they could be removed from the surface. The bacteria are covered with polysaccharides so this behaviour could be related to Gaub's group's pulling of polysaccharides from surfaces in which they also observed little resistance to lateral sliding despite a significant energy cost for vertical removal.

Mueller *et al.* (1999) *Controlled unzipping of a bacterial surface layer with atomic force microscopy*. PNAS **96**:13170

Similar to (Scheuring, 2003) but on the hexagonally packed intermediate layer of *D. radiodurans*.

Nunez *et al.* (2005) *Atomic Force Microscopy of Bacterial Communities*. Methods in Enzymology **397**:256

Image bacteria on glass (those that form biofilms on glass) and on filters whose pore size is slightly smaller than the bacteria.

Oesterhelt *et al.* (2000) *Unfolding Pathways of Individual Bacteriorhodopsins.* Science **288**:143

Imaged and unfolded individual bacteriorhodopsins from isolated purple membranes.

Schaer-Zammaretti and Ubbink (2003) *Imaging of lactic acid bacteria with AFM---elasticity and adhesion maps and their relationship to biological and structural data*. Ultramicroscopy **97**:199

Immobilized several species of bacteria on poly-L-lysine coated glass and used an array of force curves to map the elasticity of their surfaces. Bacteria with surface polysaccharides adhered more strongly to the AFM tip and were softer than those with a protein S-layer.

Scheuring *et al.* (2003) *Nanodissection and high resolution imaging of the* Rhodopseudomonas viridis *photosynthetic core complex in native membranes by AFM*. PNAS **100**:1690

Submolecular resolution of isolated *R. viridis* membranes with subsequent "nanodissection" (i.e. Probe sample with tip and pull molecules out)

Touhami *et al.* (2004) *Atomic Force Microscopy of Cell Growth and Division in* Staphylococcus aureus. Journal of Bacteriology **186**:3286

Image cell division of *S. aureus* using both AFM and thin section TEM and see interesting structural features in the AFM topographs (holes along developing septum, concentric rings in newly formed cell wall, and a meshwork in older cell wall) that were not visible in TEM. Immobilized cells on polycarbonate filter.

Velegol *et al.* (2003) *AFM Imaging Artifacts due to Bacterial Cell Height and AFM Tip Geometry.* Langmuir **19**:851

Characterize a "shadow" artifact that arises from imaging relatively high objects like bacteria with a pyramidal tip.

Bacterial Adhesion Studied with AFM:

Camesano and Logan (2000) *Probing Bacterial Electrosteric Interactions Using Atomic Force Microscopy*. Environmental Science and Technology **34**:3354

Examined effect of electrostatics, steric interactions, and surface LPS on nonlinear portion of force curves.

Ong *et al.* (1999) *Adhesion Forces between* E. Coli *Bacteria and Biomaterial Surfaces*. Langmuir **15**:2719

Use bacteria-coated tips to study adhesion on several surfaces. Find that LPS are important in adhesion.

Razatos *et al.* (1998) *Molecular determinants of bacterial adhesion monitored by atomic force microscopy*. PNAS **95**:11059

Used polyethyleneimmine-coated glass and gluteraldehyde to attach bacteria to glass and probed resultant lawn with tip. Also coated tip with bacteria and probed surfaces. Discussed effect of surface LPS.