Challenges for magnetic imaging of biogenic minerals and chromatic aberration corrected transmission electron microscopy of soft materials

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Advanced transmission electron microscopy (TEM) techniques that were originally developed for the physical sciences are increasingly being used to study biological and soft materials. One such technique is off-axis electron holography, which provides direct access to the real-space phase shift of the electron wave that has passed through a thin TEM specimen [1]. The phase shift is, in turn, sensitive to the electrostatic potential and to the in-plane component of the magnetic flux density within and around the specimen. The technique has been used to characterize the magnetic properties of ferrimagnetic magnetite (Fe_3O_4) and greigite (Fe_3S_4) crystals in magnetotactic bacteria [2]. Each crystal was found to contain a single magnetic domain, with adjacent crystals typically oriented magnetically parallel to each other to provide the bacterial cell with an overall magnetic moment that is sufficient to orient it passively in the direction of the geomagnetic field. Studies of a variety of bacterial strains, which contain crystals with different sizes, morphologies, orientations and spacings, were used to show that shape anisotropy is the most important factor controlling the magnetic microstructure of such chains of crystals, followed by interparticle interactions, with magnetocrystalline anisotropy being the least important. The phase images that are recorded using electron holography can not only be used to visualise magnetic fields, but they can also be used to provide quantitative measurements of the physical properties of individual sub-100-nm nanocrystals, such as their magnetization, coercivity and magnetic moment. Recent work has shown that the magnetic moment of an individual nanocrystal can be determined from an electron holographic phase image in a model-independent manner [3]. Key future challenges for electron holography of biogenic crystals include extending the technique to achieve higher (sub-0.5-nm) spatial resolution in the magnetic characterization of smaller (sub-5-nm) nanoparticles, ideally in three dimensions.

In the most recent generation of transmission electron microscopes, chromatic aberration (C_C) correction promises to provide improved spatial resolution and interpretability when compared with the use of spherical aberration (C_S) correction alone, primarily as a result of improvements to the temporal damping envelope of the objective lens, especially for studies of electron-beam-sensitive materials at lower accelerating voltages [4]. The reduced dependence of image resolution on energy spread in a C_C corrected microscope offers benefits for conventional bright-field and dark-field imaging as a result of the decreased influence of inelastic scattering on spatial resolution, even when using zero-loss energy filtering. Less refocusing is also necessary when moving between regions of different specimen thickness, which is advantageous for electron tomography of thick specimens, for example for imaging whole cells. For energy-filtered TEM, C_C correction allows large energy windows and large objective aperture sizes to be used without compromising the spatial resolution of energy-loss images. A further benefit of C_C correction results from the fact that combined C_S and C_C correction of the Lorentz lens of a TEM allows images to be recorded in magnetic-field-free conditions with a spatial resolution of better than 0.5 nm with the conventional TEM objective lens switched off, thereby providing an important potential route towards achieving electron holographic imaging of magnetic fields in materials with close-to-atomic spatial resolution.

[1] R. E. Dunin-Borkowski et al., in "Encyclopedia of Nanoscience and Nanotechnology", edited by H. S. Nalwa (American Scientific Publishers, 2004), pp. 41-100.
[2] R. E. Dunin-Borkowski et al., *Science* 282 (1998), 1868.
[3] M. Beleggia et al., *Ultramicroscopy* 100 (2010), 425.
[4] B. Kabius et al., *J. Electron Microsc.* 58 (2009) 147.