Magnetosome biomineralization and chain arrangement in magnetotactic bacteria

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Magnetotactic bacteria are known to form intracellular magnetic nanoparticles in organelles called magnetosomes that are arranged in one or several chains. In this study, we used a cell-suspension assay for the growth-independent study of both magnetosome formation and chain arrangement under highly controlled conditions. Mössbauer spectroscopy and electron microscopy were employed for the time-resolved analysis of the intracellular iron metabolite pattern of iron-induced magnetosome formation. Off-axis electron holography was used to study the magnetic states of the various arrangements of magnetosomes in the bacteria. Magnetite formation could be induced in iron-starved non-magnetic wild-type cells by the addition of an iron compound. By Mössbauer spectroscopy, first traces of magnetite, ferritin and ferrous iron were detected already 20 minutes after induction with $^{57}$Fe$^{3+}$-citrate. The amount of all components increased within 40 min. Then, the Fe$^{2+}$ and ferritin contributions only slightly changed whereas magnetite growth accelerated. The magnetite growth rate decelerated 215 min after induction. First crystallites were detected by TEM 55 min after iron addition, coincident with the appearance of magnetically oriented cells as detected by light-scattering measurements. TEM images showed that the first crystals formed an imperfect chain, with widely spaced magnetosomes. Over time, the average particle dimensions increased, and so did the number of crystals per cell. After less than 6 hours, the chain formation was completed, with large mature magnetosomes closely and linearly arranged. Further analyses using electron holography showed that the magnetosomes have a permanent magnetic moment once they have reached a certain size threshold and/or they are placed within ~30 nm from a mature magnetosome. Together, these data enabled us to propose a schematic model for the biomineralization of magnetosomes and their arrangement in chains.