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Submillisecond Electron Microscopic Video Imaging for Cinematic Molecular Science

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Single-molecule atomic-resolution time-resolved electron microcopy (SMART-EM) with a high-speed, high-resolution transmission electron microscope has ushered in the era of "cinematic molecular science," in which the dynamic behavior of organic and inorganic molecules can be studied through real-time video images [1, 2]. High speed imaging without increase of electron dose results in very low electron dose per frame, which often causes a very low signal to noise ratio. We have established a method to improve the image quality optimized for SMART-EM by applying the Chambolle Total Variation (CTV) denoising, which enables tracking of molecular motion with sub-millisecond temporal resolution and sub-angstrom localization precision [3]. Herein we demonstrate in-situ observation of a nanomechanical shuttling motion of a single molecule [4], and cascade reactions of nanocarbons [5,6], as applications of the high-speed SMART-EM. We also introduce a new molecular model, atomic-number-correlated (ZC) molecular model, designed for spreading the microscopic molecular imaging to chemists who are still unfamiliar to electron microscopy [7].

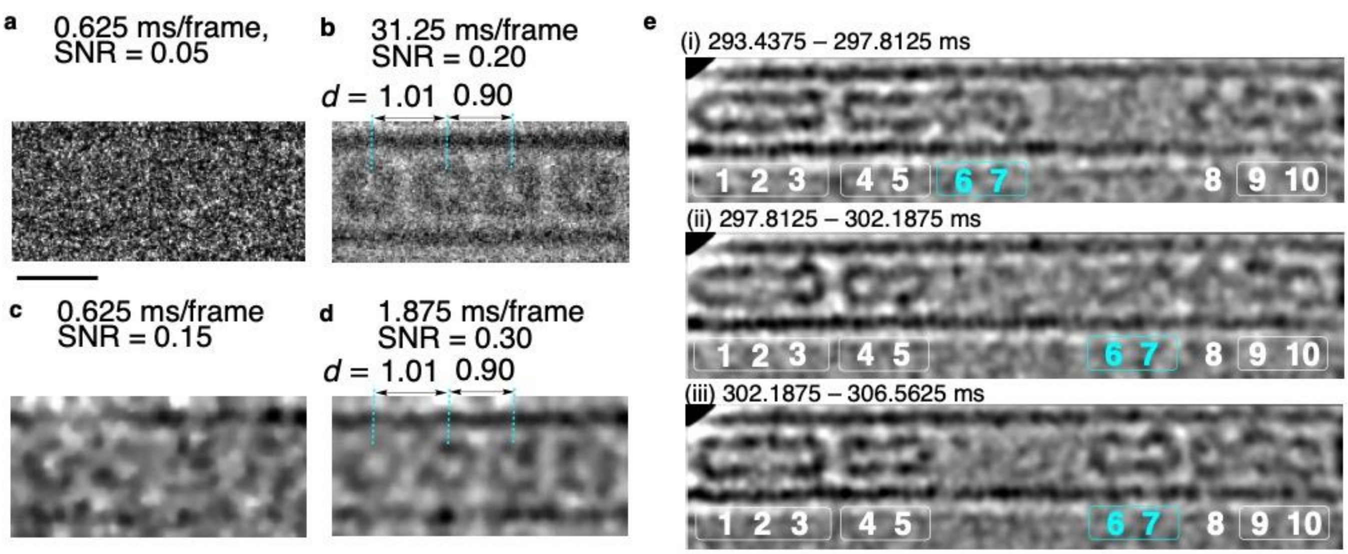

Figure 1. SMART-EM video imaging at 32–1600 fps with CTV denoising and superimposition. (a) A single-frame original image of C_{60} molecules at 423 K at 0.625 ms/frame with a direct electron detection camera (80 kV; electron dose rate (EDR) = 2.1×10^7 e^- nm^{-2} s^{-1}). (b) Fifty-frame superimposition without denoising. Distance *d* shown in nm. (c) CTV denoised single-frame image of the molecule shown in (a). (d) Three-frame superimposition of (c) (1.875 ms exposure). (e) Translation of a C_{60} dimer in a single-walled carbon nanotube (EDR = 1.4×10^7 e^- nm^{-2} s^{-1}).

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