Journal of
Nanomedicine & Nanotechnology

Sadeghi, J Nanomedic Nanotechnol 2012, 3:3
DOI: 10.4172/2157-7439.1000e105

Editorial Open Access

Hybrid Nanoparticle Systems: New Materials for Sensing and Functional Bio-Applications

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The interface between biology and nonmaterial's is an emerging frontier for research and development in science and technology. Currently significant research activities are focused on using or imitating biological materials, including self-assembly in living and synthetic materials [1], bio-functionalization of nanomaterials [2], control of cell behavior through nano-engineered materials [3], and hybrid systems consisting of biomolecules and inorganic materials, such as Metallic Nanoparticles (MNPs) and semiconductor Quantum Dots (QDs). These systems, which are of interest for various applications (including biosensors [4], responsive nanoparticle systems [5,6], etc;) are mostly based on the intrinsic resonances of QDs (excitons) and MNPs (plasmons), Forster energy transfer, and the impact of environment on biomolecules. Considerable research efforts have already been devoted to studying possible applications of such systems for biosensors that can sensitively monitor binding events in real time and can detect a variety of processes, including self-assembled monolayer formation [7], protein-ligand and antibody-protein interactions [8-9], DNA hybridization [10], and protein conformational changes [11].

An important aspect of hybrid nanoparticle systems is the prospect of having nano-scale systems that can respond uniquely to the variations in environmental conditions. A major research thrust in this regard is the investigation of nanoparticle systems in which their structural parameters are changed reversibly when the temperature, chemical or biological conditions of the environment are varied. Such systems have been fabricated by conjugating different types of nanoparticles using, for example, polymers or coiled peptides. The conjugated nanoparticles can be different types of metallic nanoparticles (gold and silver), the same type of metallic nanoparticles, and heterogeneous nanoparticles such as semiconductor nanocrystals and MNPs. Each of these systems exhibits different characteristic behavior. They can also offer respectively, enhancement of the plasmonic shift via introduction of stimulus [12], altering the intrinsic spectra shift of the plasmons [13], and detection based on controllable Forster Resonance Energy Transfer (FRET) [13,14]. Current research on heterogeneous hybrid nanosystems has already promised the possibility of nanothermometers that can detect temperature at the nanoscale [15], molecular rulers for determining conformational changes and intermolecular distances between single molecules [10], optically responsive nanoparticle complexes [5], pH detection [16], etc.

The horizon for the research and development of reversibly responsive nanoparticle systems, biological, chemical, physical nanosensors, and optical devices based on functionalities of biomolecules and inorganic nanoparticles is wide open. One major component is the possibility of blending functionalities of biomolecules with quantum coherence effects. This subject is becoming a novel research drive in nanoscience and nanotechnology, and is akin to the recent discovery of the role of quantum coherence in nature. Particularly, it is shown that in certain photosynthetic organisms, quantum coherence is used to direct the flow of energy transfer from molecule to molecule through antenna proteins [17,18]. It is believed that such a process leads to significant energy transfer efficiency. Inspired by such ground breaking discoveries, investigations that imitate this quantum-coherent electronic energy transfer in man-made structures will form a novel ground for interdisciplinary research and applications. One of the main test-beds for investigating the possibility of using the rules of quantum mechanics (quantum coherence) is hybrid systems consisting of QDs with MNPs. In fact a recent study has shown one can use these rules in such systems to control the flow of energy transfer [19].

Combination of quantum coherence in nanocrystals with plasmonic effects in MNPs and the functionalities of biomolecules also hold the promise of creating ultra-high sensitive nanosensors based on fundamentally different physical principles than conventional plasmonic or FRET-based sensors. In such nanosensors, instead of conventional means of detection of the plasmonic wavelength shift, colorimetric changes, or energy transfer, one utilizes the impact of environment on quantum coherence effects [20]. These quantum sensors can detect biological and chemical substances or can monitor nanoscale conformational changes in distinct measurable optical ways.

In spite of significant potentials of quantum sensors based on hybrid nanoparticle systems, implementation of such sensors is rather more challenging than conventional sensors. The main hurdles here are how to design nanocrystals, such that quantum coherence effects can be reached and maintained. Some of the main limiting factors are the fast damping rates of nanocrystals and fluctuations and uncertainties of the structural parameters of hybrid nanoparticle systems. The recent developments in single nanoparticle detection and spectroscopy and the possibility of designing MNPs with very high plasmonic fields, however, have rise the hope of overcoming these issues.

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Received March 30, 2012; **Accepted** March 30, 2012; **Published** April 04, 2012

Citation: Sadeghi S (2012) Hybrid Nanoparticle Systems: New Materials for Sensing and Functional Bio-Applications. J Nanomedic Nanotechnol 3:e105. doi:10.4172/2157-7439.1000e105

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