Magnetic hyperthermia behaviour of Co and reduced GO nanocomposites

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Published in Micro & Nano Letters; Received on 13th May 2019; Revised on 8th December 2019; Accepted on 24th December 2019

Co-precipitation of $CoCl_2.6H_2O$ with graphene oxide (GO) and heating at 400°C for 4 h under hydrogen resulted in the construction of cobalt/reduced GO (Co/rGO) nanocomposite utilisable in magnetic thermal therapy. Field emission scanning electron microscopy, transmission electron microscopy, X-ray photoelectron spectroscopy, vibrating sample magnetometry, thermogravimetric analysis/derivative thermogravimetry, and X-ray diffraction methods characterised the samples. Time–temperature curves of the samples containing 30, 50, 70, and 100 $\mu g\ ml^{-1}$ Co/rGO nanoparticles (NPs) suspended in phosphate-buffered saline were determined at different specific heating rates. Magnetic-field response of Co/rGO nanocomposites was better than CoNPs and GO. The biological behaviour of the powders was investigated by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assay. Co/rGO nanocomposites showed an acceptable biocompatibility behaviour, whereas the CoNPs demonstrated toxic conduct.

1. Introduction: Hyperthermia is defined as an increase of temperature in a particular area of the body to some degrees higher than the tolerable physiological level [1, 2]. This temperature enhancement is used for destruction of cancer tumours simultaneously with radiotherapy and chemotherapy, in a way that healthy cells around the tumour would not be affected [2, 3]. Among the most common methods used for thermal therapy, namely application of microwave, laser beam, or ionising beams can be mentioned which of course are used for heating and destruction of surface tumours on the skin [4–6]. All these therapy methods are useful in the destruction of cancer cells, but at last, they have some disadvantages such as the ionised-beam bad effects on the genes [7, 8].

Recently, the application of nanostructured particles in thermal therapy has attracted much attention. One application is the use of gold nanoparticles (NPs), which leads to the transformation of infrared irradiation into heat, and thus, the death of the cancer cells [9]. Gilchrist has been the first recommender of thermal therapy by magnetic-field application [10]. A variable magnetic field can alter the direction of the opposing electron spins in a magnetic NP. This alteration produces heat [11]. Rotation of the magnetic NPs within the applied field can also lead to heat production [12]. These heats, when transferred into the aimed tissue by the magnetic NPs, which are embedded into the tumour, enhance the temperature and kills the cancerous cells [13, 14].

The heat generated by the particles increases with the amplitude of the field. However, for medical and technical reasons, there are limitations to these parameters [15].

Production of a nanocomposite made of NPs plus reduced graphene oxide (GO) for utilisation in magnetic hyperthermia can improve heating efficiency by enhancement of the active specific surfaces [16, 17]. In one Letter, Yang *et al.* [18] have used iron oxide/graphene nanocomposite for its hyperthermia effects. Bai *et al.* [19] showed that the presence of graphene beside iron oxide NPs improves the magnetic hyperthermia behaviour, in addition to maintenance of magnetism in composited NPs. Previous authors have considered compounding of magnetic NPs with graphene an effective method for improvement of the thermal efficiency of the hyperthermia treatment [18–20].

Up to now, the research attention has been mostly restricted to the iron oxide/rGO nanocomposites, mainly because of their easy availability, biodegradation, and biocompatibility [21–23]. Their low cost of production is due to both ease of synthesis and their raw materials abundance. The raw materials needed for iron oxide NPs synthesis is cheaper than cobalt (Co), whereas the Co synthesis method is more complex and costly [15].

For the *in vivo* application, the concentration of the magnetic materials in the tissue should be limited to avoid the side effects [24–27]. This problem was studied in the context of magnetic resonance imaging (MRI) contrast agents, where a maximum iron concentration of 0.1 mmol/kg has been recommended [28].

The limitations concerning the particle concentration and the field parameters as well as the effect of the heat conductivity of the tissue, result in the demand of a high specific absorption rate, since high specific absorption rates imply lower time of residence of the NPs in the human body and also lower dosages to be administered to the patient.

Since the hyperthermic efficiency of a single-domain magnetic particle depends on its magneto-crystalline anisotropy, use of magnetic materials, e.g. metallic Co in Co/rGO nanocomposite with significant magnetic anisotropy and more massive magnetic moment is envisaged to allow a significant improvement in the material's efficiency. The magnetic fluid hyperthermia and the MRI are thus improved.

Another significant and unique advantage of using Co in Co/rGO nanocomposite is that it may allow reducing the particle size, which, in turn, results in additional advantages such as longer half-life time in the blood with consequently increased taken up by the reticuloendothelial system and low inorganic dose to the patient, thus decreasing particles potential toxicity [29].

This Letter presents CoNPs utilisation for the synthesis of Co/rGO nanocomposite by co-precipitation. Extensive magnetisation behaviour of Co was the reason for its selection as an alternative material for use instead of the iron oxide in hyperthermia treatment. Compositing Co particles with graphene led to the improvement of its thermal and biological behaviours. Before application in heat therapy, the synthesised nanocomposite was characterised by X-ray diffraction (XRD), transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), vibrating sample magnetometer (VSM), and thermogravimetric analysis (TGA) techniques. Thermal behaviour of a suspension containing Co/rGO against the applied magnetic field was measured. Toxicity evaluation was performed via the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) test.

2. Materials and methods

2.1. Synthesis of Co/rGO nanocomposite: GO was synthesised using Hummer's method [3]. All reagents used in this research