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Magnetic Nanoparticles: A Review of Chemical and Physical Characteristics Important in Medical Applications

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ABSTRACT

Magnetic nanoparticles (MNPs) have demonstrated their great potentials in medical applications. Technology advancements in synthesis and modification of nanoscale materials have advanced the development of different medical applications of MNPs. This paper reviews the main chemical and physical properties of MNPs important in medical applications. Pharmacokinetics and cellular adsorb of MNPs are largely associated with their physicochemical characteristics. Superparamagnetic, high magnetic susceptibility, high coercivity, non-toxicity, biocompatibility, and low Curie temperature are crucial characteristics of MNPs making them appropriate for various medical applications. The three main categories of medical applications of MNPs are targeted drug delivery, magnetic hyperthermia, and contrast agent for magnetic resonance imaging. Among the main chemical and physical properties of MNPs, the most important ones are coercivity, non-toxicity, biocompatibility, high magnetic susceptibility, and morphology, hydrodynamic size, charge, and other surface properties

Key words: Magnetic nanoparticles, Diagnosis, Treatment, Chemical properties, Physical properties

INTRODUCTION

Nanoparticles (NPs) are submicron particles with diameters ranging from 1 to 100 nm and made of inorganic or organic materials. As compared with bulk materials, NPs have many unique characteristics[1]. Although real uses of NPs in life sciences are still rarely found, great features of these materials propose a very good future for their use in this field[2-4].

Magnetic nanoparticles (MNPs) are one of the types of NPs which exhibit some response to applying magnetic field. In this regard, MNPs have various unique magnetic properties including superparamagnetic, high magnetic susceptibility, low Curie temperature, etc. In addition, these materials have been used in various industrial, medical, and environmental domains such as medical diagnosis and treatment[5, 6] magnetic fluids[7], biomedicine[7-9], catalysis[10], magnetic energy storage[11], data storage[12]. Some of important features of MNPs making them a great choice for medical applications are non-toxicity, biocompatiblilty, and high-level aggregation in the desired tissue.

In addition, applying external magnetic field causes to movement of MNPs to the desire location or induce heating because of their inducible magnetization attributes. These characteristics make them attractive for different applications including separation techniques and contrast enhancing agents for MRI to drug delivery systems, magnetic hyperthermia, etc[13-15]. Nevertheless, one of the most important problems for utilization of MNPs is to choose the materials for the made of nanostructure materials with adjustable chemical and physical attributes.

In this regard, a number of researchers suggested various forms of MNPs with different chemical compositions for some biomedical applications to utilize in some magnetic phenomena, including enhanced magnetic moments and superparamagnetic. To improve magnetic properties as well as physical behaviors of NPs, some properties such as composition, size, morphology and surface chemistry can be tailored to various processes[16,17].

Different applications require specific characteristics of MNPs. For instance, in data storage applications, the particles must be stable, switchable magnetic state to exhibit bits of information and not affected by temperature fluctuations[18, 19]. To use MNPs in therapy and biology and medical diagnosis, they must be stable in water at pH 7 and in a physiological environment. In addition, the colloidal stability of this fluid will depend strongly on the charge and surface chemistry causing both Steric and Coulombic repulsions as well as depend on the dimensions of the particles, which should be so small so that gravitation force induced precipitation can be avoided[20]. To use MNPs for biomedical applications, they must be encapsulated with a biocompatible polymer to barricade manipulation from the original structure, biodegradation and the formation of large accumulation when they are subjected to magnetic field exposure. The drugs can bind to the NPs coated with polymer by covalent attachment, entrapment on the particles or adsorption[21, 22].

The other main advantage of MNPs is their high effective surface areas and lower sedimentation rates[23-25]. The two main characteristics of MNPs to be used in biomedical applications are non-toxicity and non-immunogenicity. In addition, these particles should be small enough to maintain in the circulation and to transit via the capillary systems of tissues. To control the motion of MNPs in the blood vessels with an external magnetic field, the MNPs must have a high magnetization[26, 27]. The synthesis method of NPs can characterize the shape, the surface chemistry of the particles, the size distribution, the particle size as well as magnetic properties[28,29]. In this regard, ferri- and ferromagnetic nanoparticles synthesized by grinding bulk materials, whereas using plasma atomization and wet chemistry techniques spherical shape MNPs can be synthesized. In addition, spherical shaped particles, depending on the synthesis method, can be formed in crystalline or amorphous morphology[30, 31]. Furthermore, the synthesis method can determined new characteristics for MNPs such as high saturation field, superparamagnetic, high field irreversibility, extra anisotropy contributions[32].

The present paper focuses on the chemical and physical properties of main MNPs in medical applications. The relationships between these characteristics and their performance in different applications are discussed.

Magnetic properties of nanoparticles

The behavior of substances under an influence of an external magnetic field is determined by two factors: susceptibility and permeability. Susceptibility (χ) describes the magnetization level (M) of a material in the presence of an external magnetic field (H):

$$M = \chi H \quad ...(1)$$

The permeability indicates the magnetic induction (B) change induced by an external magnetic field (B= μH). The matter with high permeability reveals a low resistance in reaction to magnetic field[33]. All materials based on their susceptibility to magnetic fields, are categorized into several groups:

Diamagnetic

These materials in the presence of external magnetic field induce weak magnetic moment antiparallel to external field. Therefore they have small and negative susceptibility (-10^{-6} to 10^{-3}). When the external field is removed, the spins come back to initial position and they do not show magnetic features. Water, wood, quartz (SiO_2), copper, silver, and most of organic compounds are examples of diamagnetic materials. The common property of this material is that all of them have filled electronic subshells[34].

Paramagnetic

Paramagnetic substances show weak magnetic field in parallel to applied external field. The susceptibility of these is positive and in the range of (10^{-5} to10^{-3}). After elimination of external field, their magnetic moment does not persist. Aluminum, oxygen, magnesium and lithium have paramagnetic properties[35, 36].

Ferromagnetic

Ferromagnetic materials are also known as magnets have a large and positive susceptibility. The susceptibilities of ferromagnetic substance are determined by external field, temperature and their atomic structures. Unlike two other categories, their magnetic properties are persistent even after elimination of magnetic field. Indeed, after employing of strong magnetic field, the spins of substance are aligned with field. In this time, the maximum magnetization that is named saturation magnetization is obtained. When the magnitude of the field is decreased, the reduction of total magnetization is occurred due to returning of spins to their first directions. However, the magnetic moment of these materials is stable even in the zero field[37]. In addition, small ferromagnetic materials with the size in the range of tens of nanometers have one large magnetic moment. In the blocking temperature, particles can rotate freely. Therefore after elimination of external field, net magnetization is lost and it becomes zero[38]. Indeed, in this condition, they show superparamagnetic properties. They have higher magnetic susceptibilities in comparison to paramagnetic materials. By this features, they can preserve their colloidal stability and be useful for biomedical applications. As mentioned earlier, the superparamagnetic properties are observed in small particles but decreasing of size is associated by several important issues. After reduction of size, the surface effects are revealed because of increasing the surface-to-volume ratios[10].

Properties for Medical Applications
Biocompatibility and Toxicity

MNPs should be biocompatible, nontoxic, and stable for in vivo applications. These features can be controlled by changing the size and the coating's properties of nanoparticles[24, 39]. It has been shown that metallic magnetic substances (iron, nickel and cobalt) are toxic, due to their oxidation and acid erosion. For these reasons, the coating of magnetic nanoparticles to protection of them against degradation is essential[40]. For biomedical application, magnetic nanoparticles should have the ability to escape from reticuloendothelial system (RES) to reach their target. Upon administration of nanoparticles into the blood stream, the opsonization process occurs. In this process, NPs are coated with proteins of plasma and later are deleted by phagocytic cells and they cannot reach target cells[41, 42]. To avoid this event, NPs are coated by organic layer such as surfactants and polymers or inorganic species such as silica and carbon. This additional layer can increase the circulation time and colloidal stability of MNPs[43, 44].

Size of Nanoparticles

The small nanoparticles with the size in the range of 10 to 50 nm are the best selection for in vivo applications, these nanoparticles have several Benefits[45]:

1. It is possible to improve colloidal stability and avoid aggregation by reducing magnetic interaction of nanoparticles. To obtain this, the size of NPs should have superparamagnetic features. Therefore the reducing of size is necessary to achieve superparamagnetic properties.
2. The dipole-dipole interaction is proportional to the sixth power of the particle radius (r^6). Therefore by reducing size, the dipolar interactions become small and the particle aggregation is decreased.
3. Small NPs can avoid the Precipitation.
4. Small NPs have larger surface area for certain volume. It can improve the efficiency of coating and targeting process.
5. Small NPs can be stable in water at pH = 7

Saturation magnetization of magnetic nanoparticles

Having a high saturation magnetization gives NPs two abilities[45]

1. External magnetic field can control the motion of particles in the blood
2. The particles can be moved close to the targeted pathologic tissue.

CONCLUSION

This study reviewed some physical and chemical characteristic of MNPs that are crucial for medical applications. Advances in preparation of MNPs with control of their properties have introduced new particles for diagnostic applications such as utilization of MNPs in hyperthermia, magnetic drug delivery, gene delivery and magnetic resonance imaging, etc. In order to take advantage of these applications, the properties of MNPs must be known as well as their behaviors under various conditions. The success of MNPs can be affected by physicochemical properties, size, shape, and surface chemistry which can characterize their biodistribution, pharmacokinetic, and biocompatibility. To characterize and control the physicochemical properties of MNPs, we must be aware of synthesis and coating processes. Various structure models for MNPs have been reported each having some advantages. In order to synthesize new MNPs and find their behavior in the body, developing and using more advanced technologies is of prime significance.

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