Cytotoxicity of Selected Nanoparticles on Human Dental Pulp Stem Cells

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\begin{abstract}
\textbf{Introduction:} Nanoparticles are being increasingly applied in dentistry due to their antimicrobial and mechanical properties. This \textit{in vitro} study aimed to assess and compare the cytotoxicity of four metal oxide nanoparticles (TiO$_2$, SiO$_2$, ZnO, and Al$_2$O$_3$) on human dental pulp stem cells.

\textbf{Methods and Materials:} Four suspension with different concentrations (25, 50, 75, 100 µg/mL) of each nanoparticle were prepared and placed into cavities of three 96-well plates (containing 1×10$^4$ cells per well that were seeded 24 earlier). All specimens were incubated in a humidified incubator with 5% CO$_2$ at 37°C. Mosmann’s Tetrazolium Toxicity (MTT) assay was used to determine \textit{in vitro} cytotoxicity of test materials on pulpal stem cells. Cell viability was determined at 24, 48, and 72 h after exposure. Data comparisons were performed using a general linear model for repeated measures and Tukey’s post hoc test. The level of significance was set at 0.05.

\textbf{Results:} The tested nanoparticles showed variable levels of cytotoxicity and were dose and time dependant. The minimum cell viability was observed in ZnO followed by TiO$_2$, SiO$_2$ and Al$_2$O$_3$.

\textbf{Conclusion:} The results demonstrated that cell viability and morphological modifications occurred at the concentration range of 25 to 100 µg/mL and in all nanoparticles. The higher concentration and longer duration of exposure increased cellular death. Our results highlight the need for a more discrete use of nanoparticles for biomedical applications.

\textbf{Keywords:} Cytotoxicity; Dental Pulp Stem Cells; Metal Oxide Nanoparticle
\end{abstract}

\section*{Introduction}

Biomedical administrations of nanoparticles vary from gene/drug delivery and malignancy therapies to dental applications [1-3]. Nanotechnology presents a wide diversity of nanomaterial especially inorganic nanoparticles based on metal oxides and quantum dots with different morphologies like tubes, spheres, prisms and rods [4-7].

In dentistry, nanoparticles are increasingly applied due to their antimicrobial and mechanical properties [8-10]. TiO$_2$ nanoparticles are used in manufacturing of dental materials for their antibacterial activity, being chemically inert, low price, high resistance and hardness [11-13]. Previous studies demonstrated anti-biofilm activity of ZnO nanoparticles against \textit{Staphylococcus aureus} and \textit{Enterococcus faecalis} after their inclusion in mineral trioxide aggregate (MTA) formulations [14-16]. However, it is reported that the presence of ZnO nanoparticles can reduce the compressive strength of Portland cement [14]. On the other hand, addition of Al$_2$O$_3$ nanoparticles can increase flexural and tensile strength of...
composites [17]. Combination of nano CaO, Al₂O₃ and white MTA improves biological and sealing properties of MTA and also reduce its setting time [18, 19]. Furthermore, SiO₂ at low content (2 wt%) significantly intensified the mechanical properties of polyhedral oligomeric silsesquioxane nanocomposite and with the enhancement of its content, the mechanical properties declined [20].

The current expeditious growing interest in nanoparticles for biomedical applications progressively necessitates their toxicity evaluations. Despite of the above advantages, there are concerns regarding their potential adverse impact on organisms. Previous studies also indicated some toxic effects of nanoparticles [21-23] such as apoptotic and micronuclei inductive impact of nano TiO₂ [24], DNA damage and IL6 secretion enhancement by nano SiO₂ [25], and decreased viability of human lung epithelial cells and proliferation with addition of ZnO and Al₂O₃ [26]. Nevertheless, there is limited comparative information about the nanoparticles and their effects on human dental pulp stem cells (DPSCs). DPSCs are the initiative cell sources for differentiation of odontoblasts like cells to produce reparative dentin especially in vital pulp therapy approaches [27].

The present article is the first part of our comprehensive study on evaluating and developing a novel nano incorporated MTA which is mainly intended to be used for direct pulp capping and vital pulp therapy. Thus, it is necessary to investigate the potential toxicity of nanoparticles on human DPSCs.

The objectives of the present study were to specify whether nanoparticles of TiO₂, SiO₂, ZnO and Al₂O₃ affect the viability of DPSCs, to compare their cytotoxicity and to provide information for selecting the best cost effective nanoparticle to be utilized in formulation of nanohybrid MTA production as the next step.

Materials and Methods

Nanoparticles and specimen preparation

Table 1 shows the properties TiO₂, Al₂O₃, ZnO, and SiO₂ nanoparticles that were used in this study. The powder forms of these materials were suspended in sterile distilled water at a concentration of 50 mg/mL. In order to prepare a homogenous suspension, they were sonicated (S-4000 Sonicator ultrasonic processor, Misonix Inc., Farmingdale, NY, USA) at intensity of 33 W and 20 kHz frequency for 1 min. In order to prepare four concentrations of suspension of each material (25, 50, 75, 100 µg/mL), Dulbecco’s modified Eagle’s medium (DMEM) (D5030, Sigma-Aldrich, St. Louis, MO, USA) and 10% fetal bovine serum (FBS) (F6178, Sigma-Aldrich, St. Louis, MO, USA) were added and again sonicated for 2 min [28, 29].

Cell viability

For this in vitro cytotoxicity testing DPSCs were previously provided by flow cytometry and cell differentiation in Molecular and Cell Biology Laboratory of Dental Research Center, Shahid Beheshti University of Medical Sciences. After thawing process, DPSCs were cultivated in DMEM supplemented with 10% FBS, 100 U/mL penicillin, 100 µg/mL streptomycin, and 0.25 µg/mL amphotericin B (Sigma-Aldrich Corporation, St. Louis, MO), at 37°C in a 95% humidified atmosphere and 5% CO₂ [30]. After reaching proper confluence and trypsinization, 1×10⁶ cell per well were gently seeded into 96-well plates (Costar, USA) and incubated for 24 h (at 37°C, 95% humidity and 5% CO₂). Then, 200 µL of various concentration of suspensions and controls were replaced with the medium and the cells were incubated for 24, 48, and 72 h. Then 0.2% chlorhexidine was used as positive control and DMEM with the supplements as negative control. All experimental and control groups were performed in triplicate wells.

Cell culture

Dimethylthiazole-diphenyl tetrazolium bromide assay or Mosmann’s Tetrazolium Toxicity (MTT) assay was administrated for cytotoxicity evaluations. At each time point, the supernatant was rinsed by phosphate-buffered saline (PBS) (Gibco BRL, Grand Island, NY, USA). Then, 100 µL of MTT solution (Sigma-Aldrich, St. Louis, MO, USA) was added to each well. Plates were incubated for 3 h (at 37°C, 95% humidity and 5% CO₂) to permit the viable cells to convert the soluble MTT salt (yellow) into insoluble crystals of formazan (purple). Next, the supernatant cells were discarded and 100 µL of dimethyl sulfoxide (DMSO, Gibco BRL, Grand Island, NY, USA) was added to each well for dissolving the formazan crystals. The remaining stain was measured by ELISA reader (Anthos 2020, NSW, Australia) at 570 nm wavelength with 650 nm filter to determine the percentage of cell viability.

Statistical analysis

All data were analysed using SPSS 20.0.1 software (IBM, Armonk, NY, USA). After application of normality test on data, general linear model test for repeated measures ANOVA followed by the post-hoc Tukey’s tests were used for comparisons and the level of significance was set at 0.05.

Results

24 h after treatment

Figure 1A shows the difference in DPSCs viability between groups following exposure to 25, 50, 75, and 100 µg/mL suspensions of TiO₂, Al₂O₃, ZnO, and SiO₂ after 24 h. All differences between experimental and control groups were statistically significant (P<0.05) except between ZnO and TiO₂.
at 25 μg/mL concentration (P>0.05). While 90% of cell viability indicated non-toxicity, 60-90% indicated mild, 30-60% indicated moderate and less than 30%, indicated severe toxicity, respectively. Nanoparticles of Al₂O₃ were not toxic, and the others were mildly toxic compared with the negative control (P<0.05). Also, the toxicity followed a dose dependent pattern.

48 h after treatment

Figure 1B shows the difference in DPSCs viability between groups following exposure to 25, 50, 75, and 100 μg/mL suspensions of TiO₂, Al₂O₃, ZnO, and SiO₂ after 48 h. All differences between experimental and control groups were statistically significant (P<0.05). Nanoparticles of Al₂O₃ were mildly toxic, and others were moderately toxic compared with negative control (P<0.05). Also, the toxicity showed a dose and time dependent manner.

72 h after treatment

Figure 1C shows the difference in DPSCs viability between groups following exposure to 25, 50, 75, and 100 μg/mL suspensions of TiO₂, Al₂O₃, ZnO, and SiO₂ after 72 h. All differences between experimental and control groups were statistically significant (P<0.05). Although all cell viability decreased from 24 to 48 h, but none of the experimental groups showed severe toxicity. Moreover, the toxicity showed a dose and time dependent manner similar to the previous time points.

Discussion

Commercialization of nanoparticles for nanomedicine is rapidly increasing and many nanoparticle-containing products in the form of medicines, varnishes and cosmetic goods are available in the market [31]. Therefore, unexpected adverse effects of these particles is a growing concern in society [32] and academic environments [21, 33]. In the present study, we assessed and compared the in vitro cytotoxicity of TiO₂, SiO₂, ZnO, and Al₂O₃ nanoparticles on DPSCs. The results demonstrated that cell viability and morphological modifications occurred at the concentration range of 25 to 100 μg/mL and the toxicities are dose and time dependant in all four nanoparticles. The minimum cell viability was observed in ZnO followed by TiO₂, SiO₂, and Al₂O₃.

In accordance to our results, Dechsakulthorn et al. [34] indicated a dose dependent cytotoxicity of ZnO nanoparticles and TiO₂ nanoparticles via Non-Radioactive Cell Proliferation (MTS) assay. Also, higher toxicity of ZnO nanoparticles compared to TiO₂ nanoparticles was reported. Zheng et al. [35] reported that presence of nano ZnO significantly inhibited L929 mouse fibroblasts and Hela cells proliferation via MTT assay, cell flow cytometry, light and electron microscopy evaluations. Moreover, they feed 30 mice suspension of nano ZnO (30 mg/mL) through digestive tract and observed glomerular swelling in kidney, inflammation in heart and hydropic degeneration in liver. However, the combination of nano-scale ZnO in zinc-oxide eugenol sealer showed the same biocompatibility compared to Pulpdent (commercially available ZOE-based sealer) by MTT assay [36]. In vivo experiments demonstrated adverse effects of Zn and TiO₂ nano-powder in mice at 5 g/kg body weight [37, 38] and pulmonary toxicity of TiO₂ nanoparticles in rats at 5 mg/kg concentration after inhalation [39]. Inhalation is the most common route of exposure among these studies [40, 41] which is not necessarily important for dental material applications. For instance, Heravi et al. [42] reported lower toxicity of nano-scale TiO₂ containing orthodontic adhesives compared with conventional adhesives and indicated that the addition of 1 wt% TiO₂ nanoparticles into a conventional adhesive did not entail extra health concerns in comparison with conventional pure resin.

Pakrashi et al. [43] demonstrated the cytotoxicity of Al₂O₃ nanoparticles for bacteria at very low concentration (less than 1 μg/mL). This fact together with our results can suggest the potential administration of this nanoparticle as an antibacterial agent in dentistry. In addition, even the biocompatibility of dental materials containing Al₂O₃ nanoparticles can be promoted by addition of hydroxyapatite [44].

In agreement with our results, Gong et al. [4] indicated the dose dependent reduction of cell viability after exposure to nano and micro sized SiO₂ within HaCaT cells. However, Afsharnezhad et al. [45] showed that the application of SiO₂ nanoparticles can even improve the level of biocompatibility of a cyanoacrylate composite in addition to promotion of its mechanical properties.

| Table 1. Nanoparticle characteristics |
|---------------------------------------|
| Product name | Form | Particle size (nm) | Surface area (m²/g) | Manufacturer |
|----------------|------|-------------------|---------------------|-------------|
| Titanium (IV) oxide | Nano powder | 21 | 35-65 | Sigma-Aldrich Corporation |
| Aluminium oxide | Nano powder | <50 | >40 | Sigma-Aldrich Corporation |
| Zinc oxide | Nano powder | <100 | 12-25 | Sigma-Aldrich Corporation |
| Silicon dioxide | Nano powder | 5-15 | 590-690 | Sigma-Aldrich Corporation |
According to a literature review, few studies have compared the cytotoxicity of different nanoparticles at the same time. In 2010, Kim et al. [26] conducted a comparative cytotoxicity study on TiO$_2$, CeO$_2$, ZnO, and Al$_2$O$_3$. In accordance with our results they reported a dose and time dependent toxicity effect and Al$_2$O$_3$ nano powder was less toxic than others and ZnO had the most toxicity. Furthermore, Qiang et al. [28] conducted a comparative study between cytotoxicity of TiO$_2$, SiO$_2$, ZnO, and Al$_2$O$_3$ nanoparticles on human fetal lung fibroblasts. They also reported ZnO nanoparticles as the most toxic one. However, in their study all evaluations were performed after 48 h, so time dependent toxicity assessment is not possible.

Jaberiansari et al. [46], showed that an experimental nano hybrid MTA is severely toxic at neat concentration after 24, 48, and 72 h and also moderately toxic at 1/2 concentration on DPSCs. They did not mention the components of their experimental nano hybrid MTA. So, their comparison and judgment about nanoparticles and their percentages with other studies is not possible.

However, because of the presence of many confounding covariates in the oral cavity, these results of in vitro investigations might not be thoroughly generalized to the clinical applications and more in vivo and clinical trials are needed for making an evidence based decisions.

**Conclusion**

As the first step in comprehensive research for application of nanoparticles in dental materials especially MTA, we conclude that due to dose and time dependent toxicity of these nanoparticles, especial attention to safe administration of them is needed. It may be solved by using low-concentration incorporation with biocompatible dental materials. Based on the differential toxicity of these materials, further investigations are required to find better substitutions.

![Figure 1. Percentage of DPSCs viability (mg/mL) after exposure to 25, 50, 75, and 100 μg/mL at: A) 24; B) 48 and C) 72 h](image-url)
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Conflict of Interest: ‘None declared’.

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