Effect of nanostructured TiO$_2$ crystal phase on photoinduced apoptosis of breast cancer epithelial cells

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**Purpose:** The use of nanoparticles has seen exponential growth in the area of health care, due to the unique physicochemical properties of nanomaterials that make them desirable for medical applications. The aim of this study was to examine the effects of crystal phase-nanostructured titanium dioxide particles on bioactivity/cytotoxicity in breast cancer epithelial cells.

**Materials and methods:** Cultured Michigan Cancer Foundation (MCF)-7 and human breast adenocarcinoma (MDA-MB-468) breast cancer epithelial cells were exposed to ultraviolet A light (wavelength 350 nm) for 20 minutes in the presence of aqueous dispersions of two different nanostructured titanium dioxide (TiO$_2$) crystal phases: anatase and an anatase–rutile mixture. Detailed characterization of each titanium dispersion was performed by dynamic light scattering. A 3-(4,5-dimethylthiazol-2-yl)-2,5 diphenyltetrazolium bromide (MTT) colorimetric assay was employed to estimate the percentage of viable cells after each treatment. Western blot analysis of protein expression and characterization, as well as a deoxyribonucleic acid (DNA)-laddering assay, were used to detect cell apoptosis.

**Results:** Our results documented that 100% anatase TiO$_2$ nanoparticles (110–130 nm) exhibited significantly higher cytotoxicity in the highly malignant MDA-MB-468 cancer cells than anatase–rutile mixtures (75%/25%) with the same size. On the contrary, MCF-7 cells (characterized by low invasive properties) were not considerably affected. Exposure of MDA-MB-468 cells to pure anatase nanoparticles or anatase–rutile mixtures for 48 hours resulted in increased proapoptotic Bax expression, caspase-mediated poly(adenosine diphosphate ribose) polymerase (PARP) cleavage, DNA fragmentation, and programmed cell death/apoptosis.

**Conclusion:** The obtained results indicated that pure anatase TiO$_2$ nanoparticles exhibit superior cytotoxic effects compared to anatase–rutile mixtures of the same size. The molecular mechanism of TiO$_2$ nanoparticle cytotoxicity involved increased Bax expression and caspase-mediated PARP inactivation, thus resulting in DNA fragmentation and cell apoptosis.

**Keywords:** nanostructured TiO$_2$, anatase, rutile, photocatalysis, breast cancer epithelial cells, apoptosis

**Introduction**

Nanoparticles have unique physicochemical properties and functionalities that are different from their bulk counterparts.$^{1,2}$ In recent years, there has been increased concern about nanotoxicology and the factors that are intertwined with it. Due to the importance of this size class of particles, there is a need for clarification and better understanding of nanoparticle physicochemical properties and their cytotoxic potential.$^{3–5}$

Titanium is widely used in biomedical applications, due to its mechanical properties and biocompatibility, and of course for photocatalysis purposes.$^{6,7}$ It is now well established that photoexcited titanium dioxide (TiO$_2$) can drive various chemical
These contained nanoparticles of similar sizes and different particle, TiO₂, the effect of the particle crystal phase of a model nanoparticle, quantum dots, indicate that their toxicity is related to ROS production. In vivo studies to determine the intrinsic potential of particles to generate ROS, the photocatalytic properties of TiO₂, specifically, was used to determine the size-distribution profile of small suspensions and solution, as well as other physicochemical properties, such as zeta potential. The fundamentals of this method are based on the fact that when light hits small particles, it scatters in all directions (Rayleigh scattering), as long as the particles are small compared to the wavelength (below 250 nm). In the case of laser as a light source, which...
is monochromatic and coherent, a time-dependent fluctuation in scattering intensity is observed.

In particular, DLS measurements were performed on aged titanium dispersions (10 days after preparation) after filtering the solutions through a 0.45 μm filter (Merck Millipore), in order to estimate size at 25°C, with a rate of approximately 170 kilocounts/second, attenuator at the seventh level, and measurement duration of 80 seconds. Sample preparation, either by filtration or centrifugation, was performed in order to remove dust and artifacts from the solution.

Also, measurements for zeta potential were performed, at 25°C, with a rate of approximately 300 kilocounts/second, attenuator at the seventh level, and 12 zeta runs. An ALV/CGS-3 compact goniometer system (ALV, Hesse, Germany) was used, equipped with an He–Ne laser, operating at 632.8 nm, which was interfaced with an ALV-5000/ EPP multi-tau digital correlator with 288 channels and an ALV/LSE-5003 light-scattering electronics unit for stepper-motor drive and limit-switch control.

**Cell-viability analysis (MTT assay)**

The 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-tetrazolium bromide (MTT) colorimetric assay was used to determine cell viability. The MTT assay is based on the ability of a mitochondrial dehydrogenase enzyme from viable cells to cleave the tetrazolium rings of the pale-yellow MTT and form dark-blue formazan crystals that are largely impermeable tocell membranes, thus resulting in crystal accumulation within healthy cells. Lysis of cells by the addition of a detergent results in the liberation of the crystals, which then become soluble. The number of viable cells is directly proportional to the level of the formazan product created. The color was quantified using a simple colorimetric assay, with the use of a multiwell scanning spectrophotometer (enzyme-linked immunosorbent assay reader).

For the MTT assays, MCF-7 and MDA-MB-468 cancer breast cells (~6,000 cells/well) were seeded in 96-well plates, using Dulbecco’s Modified Eagle’s Medium, as previously mentioned. Twenty-four hours after plating, various concentrations of the two TiO₂ dispersions of different crystal structure were added to the appropriate samples, and the samples were irradiated using UVA light (wavelength 350 nm) for 20 minutes. The cells were further cultured for 48 hours. On the day of the viability assay, fresh medium (~100 μL/well) and MTT solution (5 mg/mL in phosphate-buffered-saline [PBS]) was added to each well, and the plates were incubated at 37°C for at least 3 hours. At the end of the incubation period, the medium and MTT solution were removed from each well and dimethyl sulfoxide was added. The 96-well plates were then gently shaken for 30 minutes. In this type of experiment, optical density was measured at 590 nm. The percentage of viability was calculated compared with untreated control (100% viability).

The experiment was repeated several times, in order to determine the minimal time of UV activation of titanium dispersions and the optimal concentration of TiO₂. The appropriate conditions were selected, and the experiment for examining titanium effects repeated at least five times in quadruplicate. In all instances, similar results were obtained.

**Western blotting**

To examine the effects of TiO₂ dispersions on caspase-mediated poly(adenosine diphosphate ribose) polymerase (PARP) cleavage indicating selective cell apoptosis, Western blotting experiments were performed. Cells were scraped into PBS, washed twice with PBS, resuspended in 3-(3-cholamidopropyl)dimethylammonio)-1-propanesulfonate buffer containing a 1% (volume/volume) protease-inhibitor cocktail (P8340; Sigma-Aldrich) and lysed by repeated (three times) freezing and thawing.

The expression of Bcl-2, Bax, Bad, and Bcl-xL and assessment of their levels was also studied. Cells were washed in PBS and lysed in lysis buffer containing 20 mM Tris-HCl (pH 7.5), 1% Triton X-100, 150 mM NaCl, 1 mM EDTA (pH 8.0), 10 mM NaF, 1 mM Na₂VO₄, 1 mM PMSF (phenyl methyl sulfonyl fluoride), and the protease-inhibitor cocktail.

A Bradford colorimetric assay (Thermo Fisher Scientific) was utilized to estimate total protein concentration. Equal amounts of total protein of cell lysates were separated by sodium dodecyl sulfate (SDS) polyacrylamide gel electrophoresis and transferred to Hybond enhanced chemiluminescence nitrocellulose membranes (GE Healthcare UK Ltd, Little Chalfont, UK). Membranes were probed with anti-PARP (9542; Cell Signaling Technology, Danvers, MA, USA), anti-Bcl-2 (sc-7382), anti-Bcl-xL (sc-8392), anti-Bax (sc-6236), and anti-Bad (sc-942) (Santa Cruz Biotechnology, Dallas, TX, USA) antibodies. Proteins were detected with an enhanced chemiluminescence detection system (Thermo Fisher Scientific) after incubation with horseradish peroxidase-conjugated secondary antibodies (GE Healthcare). To ensure equal amounts of protein loading, the blots were stripped (Re-Blot Plus Western blot stripping solution; Merck Millipore) and reprobed with anti-β-tubulin monoclonal antibodies.
Results were obtained from three independent experiments for each type of TiO₂ dispersion.

**DNA-laddering assay**
To establish the effects of TiO₂ dispersions on apoptotic cell death, deoxyribonucleic acid (DNA) was isolated, electrophoresed in agarose gel, and images of intact and/or laddered DNA were obtained. Briefly, cells were gently scraped in culture medium and centrifuged at approximately 2,000 rpm at room temperature. The pellet was then washed in PBS, centrifuged again, and cells lysed in DNA-extraction buffer containing 1% nonyl phenoxypolyethoxylethanol (NP)-40, 1% SDS, 10 mM EDTA, and 50 mM Tris-HCl (pH 7.5). Subsequently, ribonuclease A and proteinase K were added and the lysates left overnight at 50°C. Ammonium acetate (2.5 M) was then added and lysates mixed thoroughly. DNA was precipitated with ice-cold ethanol, and the pellet was washed again in ethanol, air-dried at room temperature, and dissolved in Tris–EDTA buffer containing 1 mM EDTA and 10 mM Tris-HCl (pH 7.4). DNA concentration was determined, their size as a function of intensity is shown in Figure 1, A and C, and the zeta potential in Figure 1, B and D, respectively. The same mean values were estimated by DLS analysis of size, as a function of volume, and as a function of number of nanoparticles (data not shown).

The average size was about 111.3 nm for TiO₂ 100% anatase and 138.5 nm for Evonik TiO₂ P25 (Figure 1, A and C). Figure 1B shows that there are four distinct peaks dividing the zeta potential (peak 1, −33.1 mV; peak 2, −20.8 mV; peak 3, −10.9 mV; peak 4, −2 mV) of TiO₂ 100% anatase, with zeta potential of −16.7±9 mV, while in the case of Evonik

**Statistical analysis**
Values are presented as means ± standard deviation. Statistically significant differences between values were evaluated by one-way analysis of variance and the nonparametric Kruskal–Wallis method in the SPSS program (IBM Corporation, Armonk, NY, USA) as appropriate. P<0.05 was considered statistically significant.

**Results**

**Photocatalyst characterization**
DLS provides insight into the dynamic properties of soft materials by measuring single scattering events, meaning that each detected photon has been scattered by the sample exactly once. Actually, DLS makes use of spectral analysis in order to observe the dynamic properties that characterize colloidal dispersions of particles, and it is a commonly used technique for the determination of particle size in the submicron range. In this study, DLS was used to characterize the size and zeta potential of Evonik TiO₂ P25 and Sigma-Aldrich TiO₂ (100% anatase) nanoparticles.

The pH of Sigma-Aldrich TiO₂ (100% anatase) was 6.8, and the pH of Evonik TiO₂ P25 was 7.1. The distribution of their size as a function of intensity is shown in Figure 1, A and C, and the zeta potential in Figure 1, B and D, respectively. The same mean values were estimated by DLS analysis of size, as a function of volume, and as a function of number of nanoparticles (data not shown).

The average size was about 111.3 nm for TiO₂ 100% anatase and 138.5 nm for Evonik TiO₂ P25 (Figure 1, A and C). Figure 1B shows that there are four distinct peaks dividing the zeta potential (peak 1, −33.1 mV; peak 2, −20.8 mV; peak 3, −10.9 mV; peak 4, −2 mV) of TiO₂ 100% anatase, with zeta potential of −16.7±9 mV, while in the case of Evonik

**Figure 1** Characterization of TiO₂ nanoparticles.
**Notes:** Distribution of the hydrodynamic diameter (d, or 2r) of (A) Sigma-Aldrich TiO₂ 100% anatase and (C) Evonik TiO₂ P25 nanoparticles obtained by DLS. Distribution of zeta potential of (B) Sigma-Aldrich TiO₂ 100% anatase and (D) Evonik TiO₂ P25 nanoparticles obtained by DLS. Analysis was performed from the stock solution. Evonik TiO₂ P25; Evonik Industries, Essen, Germany. Sigma-Aldrich TiO₂; Sigma-Aldrich Co., St Louis, MO, USA.
**Abbreviation:** DLS, dynamic light scattering.
TiO$_2$ P25 there are two peaks (peak 1, −23.7 mV; peak 2, −9.09 mV) with zeta potential of −11.7±8 mV (Figure 1D).

Additionally, micro-Raman spectra were recorded in the backscattering configuration using an inVia Reflex system (Renishaw, Wotton-under-Edge, UK) equipped with a diode laser at 785 nm excitation (Figure 2). The scattered light was filtered by a dielectric edge Rayleigh rejection filter with cutoff at 100 cm$^{-1}$ and analyzed with a 1,200 line/mm diffraction grating. The laser beam was focused on the sample surface using the long working distance (8 mm) objective with magnification of 50× with a DM LM microscope (Leica Microsystems, Wetzlar, Germany). The nominal spot size of the laser beam was about 1 μm, and the power density on the sample was controlled to 0.5 mW/μm$^2$ with a filter.

The spectra of the Sigma-Aldrich TiO$_2$ show only the anatase-vibration peaks centered at 144, 196, 394, 516 and 637 cm$^{-1}$. Besides anatase, the Raman spectra of Evonik P25 also show the presence of the rutile TiO$_2$ phase, evidenced by two extra broad peaks at 446 and 612 cm$^{-1}$. Neither position (144 cm$^{-1}$) nor line width (9.5 cm$^{-1}$) of the strongest anatase Raman mode showed any difference for the two samples, and were characteristic for large crystal size, above 20 nm (Figure 2).

**Effect of photoexcited TiO$_2$ nanoparticles on cell viability**

The MTT assay was utilized to evaluate the effects of TiO$_2$ on the viability of both MCF-7 and MDA-MB-468 cells. Cells were incubated with increasing concentrations of TiO$_2$ dispersions (100% anatase or anatase 75%–rutile 25% mixture) for 48 hours, and the percentage of cell viability was estimated as a function of the photocatalyst concentration. Cell viability (L) was calculated as $L = \frac{ABS_{treated}}{ABS_{untreated}} \times 100\%$ (1) and

$$\delta L = \left( \frac{\partial L}{\partial ABS_{treated}} \delta ABS_{treated} \right)^2 + \left( \frac{\partial L}{\partial ABS_{untreated}} \delta ABS_{untreated} \right)^2$$

where $ABS_{treated}$ and $ABS_{untreated}$ are the mean absorption values at 590 nm for the treated and untreated samples, respectively.

As shown in Figure 3A, cell viability gradually decreased as the concentration of Sigma-Aldrich TiO$_2$ 100% anatase increased. In particular, a concentration of 20 μM TiO$_2$ reduced MDA-MB-468 cell viability by 45%, while the same dose affected only 25% of the MCF-7 cell population (Figure 3A). The effect of Sigma-Aldrich TiO$_2$ 100% anatase on cell viability was further enhanced by UV irradiation (Figure 3C). In the presence of 20 μM of UVA-irradiated TiO$_2$ 100% anatase, MDA-MB-468 cell viability was reduced by 70%, while the same dose affected 40% of MCF-7 cells (Figure 3C).

In addition, a progressive reduction in cell viability was observed in the presence of increased doses of Evonik TiO$_2$ P25. Specifically in the case of MDA-MB-468 cells, a concentration of 20 μM reduced cell viability to 60%, while the relevant percentage of MCF-7 cell viability was 80% (Figure 3B). In the presence of 20 μM of UVA-irradiated Evonik TiO$_2$ P25, MDA-MB-468 cells exhibited 40% viability, whereas the corresponding percentage in MCF-7 cells was 80% (Figure 3D). UV irradiation by itself exerted a minor effect on cell viability (about 10%) (Figure 3, C and D).

Taken together, these results indicate that the highly malignant MDA-MB-468 cancer cells are more susceptible to cell death when exposed to UVA-activated TiO$_2$ nanoparticles compared to MCF-7 cells, which are characterized by low metastatic potential. Moreover, TiO$_2$ composed of 100% anatase had a higher cytotoxic effect compared to the effect of Evonik TiO$_2$ P25.

**Effect of photoexcited TiO$_2$ nanoparticles on caspase-mediated PARP cleavage**

Activation of caspases is associated with morphological and functional changes taking place during cell apoptosis. PARP (113 kDa), is one of the main cleavage targets of activated...
caspases, and participates in DNA repair following exposure to stress.\textsuperscript{28-30} Cleavage of PARP results in loss of the enzymatic DNA-repair function,\textsuperscript{31} thus providing a marker of cells undergoing apoptosis.\textsuperscript{32}

PARP cleavage was examined by Western blot analysis in cells treated with UV-activated dispersions of Evonik TiO\textsubscript{2} P25 or Sigma-Aldrich TiO\textsubscript{2} 100% anatase. Lysates from cells treated for 24 hours with cisplatin (1 mg/mL) were used as a positive control for the induction of PARP cleavage. As shown in Figure 4, A and B, in cells treated with Sigma-Aldrich TiO\textsubscript{2} 100% anatase or photoexcited TiO\textsubscript{2} nanoparticles, PARP cleavage was remarkably increased compared to control cells, confirming that treatment with Sigma-Aldrich TiO\textsubscript{2} 100% anatase nanoparticles induced apoptosis in MDA-MB-468 cells; on the contrary, TiO\textsubscript{2} 100% anatase did not affect PARP cleavage in MCF-7 cells (Figure 4, C and D). Figure 5, A and B show that only photoexcited Evonik TiO\textsubscript{2} P25 treatment resulted in PARP cleavage in MDA-MB-468 cells compared to the control group. However, the effect of photoexcited Evonik TiO\textsubscript{2} P25 on PARP cleavage was less than that obtained by TiO\textsubscript{2} 100% anatase. PARP cleavage was not detected in MCF-7 cells under the same conditions (Figure 5, C and D).

In summary, our results indicated that photoexcited TiO\textsubscript{2} nanoparticles induced apoptosis specifically in MDA-MB-468 cells. This effect was enhanced in cells treated with TiO\textsubscript{2} 100% anatase nanoparticles compared to cells treated with Evonik P25 TiO\textsubscript{2}.

**Effect of photoexcited TiO\textsubscript{2} nanoparticles on Bcl-2 family protein expression**

Bcl-2 family proteins play a pivotal role in the regulation of cell apoptosis. It is also argued that some Bcl-2 family proteins can induce (proapoptotic members) or inhibit (antiapoptotic members) the release of cytochrome C into the cytosol, which in turn activates caspase-9 and caspase-3, thus leading to apoptosis.\textsuperscript{33,34} Therefore, we examined the effects of TiO\textsubscript{2} on the expression of Bcl-2, Bcl-x\textsubscript{L} (antiapoptotic factors), Bax, and Bad (proapoptotic factors). Cells were treated with UV-activated dispersions of Sigma-Aldrich TiO\textsubscript{2} 100% anatase and Evonik TiO\textsubscript{2} P25, and cell lysates were immunoblotted with anti-Bcl-2, anti-Bcl-x\textsubscript{L}, anti-Bax, and anti-Bad antibodies. Lysates from cells treated for 24 hours with cisplatin (1 mg/mL) were used as a positive control for apoptosis.

Representative Western blots of Bcl-2, Bax, Bcl-x\textsubscript{L}, and Bad expression in MDA-MB-468 cells and MCF-7 cells are shown in Figure 6, A and C, respectively. Photoexcited TiO\textsubscript{2} 100% anatase and Evonik P25 nanoparticles induced specifically in MDA-MB-468 cells an increase in Bax expression.
**Figure 4** Photoexcited TiO$_2$ 100% anatase (Sigma-Aldrich) nanoparticles induced caspase-mediated PARP cleavage.

**Notes:** Representative Western blots of uncleaved and cleaved PARP of (A) MDA-MB-468 cells and (C) MCF-7 cells. Blots were stripped and reprobed with anti-tubulin antibody to normalize the blots for protein levels. Densitometric quantification of cleaved/uncleaved PARP to tubulin levels for (B) MDA-MB-468 cells and (D) MCF-7 cells.

*P* < 0.05 compared to cleaved/uncleaved PARP/tubulin levels of untreated cells. Lysates of cells treated for 24 hours with cisplatin (1 mg/mL) were used as positive control for the induction of PARP cleavage. Data represent means ± standard deviation from three independent experiments. Sigma-Aldrich TiO$_2$; Sigma-Aldrich Co., St Louis, MO, USA.

**Abbreviations:** MCF, Michigan Cancer Foundation; MDA-MB-468, human breast adenocarcinoma; UV, ultraviolet; PARP, poly(adenosine diphosphate ribose) polymerase.

**Figure 5** Photoexcited Evonik TiO$_2$ P25 nanoparticles induced caspase-mediated PARP cleavage.

**Notes:** Representative Western blots of uncleaved and cleaved PARP of (A) MDA-MB-468 cells and (C) MCF-7 cells. Blots were stripped and reprobed with anti-tubulin antibody to normalize the blots for protein levels. Densitometric quantification of cleaved/uncleaved PARP to tubulin levels for (B) MDA-MB-468 cells and (D) MCF-7 cells.

*P* < 0.05 compared to cleaved/uncleaved PARP/tubulin levels of untreated cells. Lysates of cells treated for 24 hours with cisplatin (1 mg/mL) were used as positive control for the induction of PARP cleavage. Data represent means ± standard deviation from three independent experiments. Evonik TiO$_2$, P25; Evonik Industries, Essen, Germany.

**Abbreviations:** MCF, Michigan Cancer Foundation; MDA-MB-468, human breast adenocarcinoma; UV, ultraviolet; PARP, poly(adenosine diphosphate ribose) polymerase.
Figure 6: Photoexcited TiO$_2$, 100% anatase and Evonik P25 nanoparticles increased Bax expression in MDA-MB-468 cells.

Notes: Representative Western blots of Bcl-2, Bax, Bcl-x$_L$, and Bad expression in (A) MDA-MB-468 cells and (C) MCF-7 cells. Blots were stripped and reprobed with anti-tubulin antibody to normalize the blots for protein levels. Densitometric quantification of Bcl-2/tubulin, Bax/tubulin, Bcl-x$_L$/tubulin and Bad/tubulin as fold over basal rate (control cells) in (B) MDA-MB-468 cells and (D) MCF-7 cells. *P<0.05 versus control cells. Lysates of cells treated for 24 hours with cisplatin (1 mg/mL) were used as positive control for induction of Bcl-2 family protein expression. Data represent means ± standard deviation from three independent experiments. Evonik TiO$_2$, P25; Evonik Industries, Essen, Germany. Sigma-Aldrich TiO$_2$, Sigma-Aldrich Co., St Louis, MO, USA.

Abbreviations: MCF, Michigan Cancer Foundation; MDA-MB-468, human breast adenocarcinoma; UV, ultraviolet; TiO$_2$(S), Sigma-Aldrich TiO$_2$, 100% anatase; TiO$_2$(E), Evonik TiO$_2$, P25.

Effect of photoexcited TiO$_2$ nanoparticles on DNA fragmentation

DNA fragmentation detected by electrophoresis (DNA-laddering assay) is a commonly used method for separation of DNA fragments based on their size and charge.$^{35-40}$ Therefore, the effect of TiO$_2$ nanoparticles on DNA damage in breast cancer epithelial cells was qualitatively evaluated using the DNA-laddering assay. We observed that significant DNA damage (fragmentation) was induced after treatment of MDA-MB-468 cells with photoexcited Sigma-Aldrich TiO$_2$, 100% anatase, although Evonik TiO$_2$, P25 also induced DNA laddering, but to a lesser extent compared to TiO$_2$, 100% anatase (Figure 7A). The pattern of DNA laddering was similar to that obtained from cells treated for 24 hours with cisplatin (1 mg/mL) (Figure 7A). Control cells or cells treated with either UVA or unirradiated TiO$_2$, 100% anatase exhibited no significant DNA fragmentation, as indicated by the presence of a wide genomic DNA band on the top of agarose gel. In MCF-7 cells, neither Sigma-Aldrich TiO$_2$, 100% anatase nor Evonik TiO$_2$, P25 induced DNA damage, as indicated by the absence of a DNA-laddering pattern (Figure 7B). Taken together, these results (Figure 7) are well correlated with results obtained from the analysis of PARP cleavage (Figures 4 and 5) and Bax expression (Figure 6) insofar as apoptosis is concerned.

Discussion

The present study demonstrates that the cytotoxicity of TiO$_2$ nanoparticles depends on the crystal phase of TiO$_2$ particles, and also establishes the apoptotic potential of TiO$_2$ nanoparticles in two different breast cancer epithelial cell lines: the highly malignant MDA-MB-468 and MCF-7 cells, which have low metastatic potential.
Previous studies in various animal and human cell lines demonstrated that TiO$_2$ nanoparticles generate a large amount of hydroxyl free radicals, thereby leading to DNA damage.$^{41,42}$ It has been proposed that the genotoxicity of metals and metal oxides results from the indirect formation of ROS. Protonation of O$_2^·$ radicals can produce hydroxyl and peroxy radicals (OH, H$_2$O$_2$), which in turn can convert fatty acids to toxic lipid peroxides, destroying biological membranes.$^{43}$ Moreover, amorphous TiO$_2$ particles produced more ROS than anatase TiO$_2$ particles of the same size.$^{21,22}$ In addition, it was unambiguously shown that 100% anatase TiO$_2$ particles (40–50 nm) resulted in higher ROS activities than anatase–rutile mixtures of the same size.$^{21,44}$ In addition to anatase–rutile mixtures, rutile TiO$_2$ particles also lead to decreased ROS activity compared to both amorphous and anatase TiO$_2$. It appears then that ROS activity of anatase–rutile TiO$_2$ decreased as the fraction of rutile increased.

Based on the hypothesis that crystallinity will affect oxidant generation,$^{21}$ we investigated whether the cytotoxicity of TiO$_2$ nanoparticles depends on the crystal phase. The effect of the crystal phase on TiO$_2$ activity was evaluated by comparing nanotoxicity of TiO$_2$ dispersions with nanoparticles of similar sizes and different nanostructure, namely anatase (100%) and Evonik P25 (anatase–rutile mixture [75%:25%]). Since these nanoparticles create aggregates, increasing their final size in the dispersion, ultrasonication was used to eliminate aggregation in aqueous suspensions and reduce their size.$^{45-48}$ Three different mechanisms—rupture, erosion, and shattering of nanoparticle cluster breakup—were reported by Özcan-Taşkin et al.$^{49}$ Following ultrasonication, characterization of TiO$_2$ 100% anatase and Evonik P25 nanoparticles was performed to explore properties of the materials used in this study. DLS was used to characterize the size of TiO$_2$ nanoparticles. Periodic DLS measurements of the samples showed that the particle aggregates remained quite stable, as their hydrodynamic radius did not increase for a period of more than a week.$^{50}$ The average size was about 111.3 nm for TiO$_2$ 100% anatase and 138.5 nm for Evonik TiO$_2$ P25, thus the two dispersions were of the same order of magnitude. The zeta potential of both dispersions was also quite similar: −16.7±9 mV for TiO$_2$ 100% anatase, and −11.7±8 mV for Evonik TiO$_2$ P25.

Our results demonstrated that TiO$_2$ 100% anatase was more efficient in inducing apoptotic cell death in MDA-MB-468 cells than Evonik TiO$_2$ P25. Apparently then, the highly malignant MDA-MB-468 cancer cells are more susceptible to UVA-activated TiO$_2$ nanoparticle-induced cell death compared to MCF-7 cells. It is possible then that the higher cytotoxic activity of TiO$_2$ 100% anatase is a consequence of its pure anatase nanostructure. Our results are in agreement with the findings of Sayes et al.$^3$ who demonstrated that nano-TiO$_2$ particles in the anatase phase generated the most ROS and the greatest cytotoxic responses following in vitro exposure of human dermal fibroblasts or A549 human lung epithelial cells. They concluded that the nano-TiO$_2$ particles in the anatase crystal phase were more efficient as photocatalysts compared to the rutile particles, due to inherent differences in the crystal structure of the two phases.$^9$

Caspases are involved in the implementation of apoptotic process, since activation of these proteins result in impaired...
cell function.\textsuperscript{58,51} PARP is one of the main cleavage targets of caspases. During apoptosis, PARP is cleaved into 89 kDa and 24 kDa fragments that are inactive, since the small fragment containing the DNA-binding domain of cleaved PARP may inhibit access by other repair enzymes.\textsuperscript{52} The 89 kDa fragment is localized to the nucleoplasm during apoptosis, in order to modulate the activity of other proteins involved in apoptosis, such as p53.\textsuperscript{31,33}

Analysis of caspase-mediated PARP cleavage revealed that in MDA-MB-468 cells treated with TiO\textsubscript{2} 100% anatase or photoexcited TiO\textsubscript{2} 100% anatase nanoparticles, PARP cleavage was remarkably increased, confirming that TiO\textsubscript{2} 100% anatase nanoparticles induced apoptosis in MDA-MB-468 cells; under the same conditions, PARP cleavage was not detected in MCF-7 cells. Similarly, photoexcited Evonik TiO\textsubscript{2} P25 treatment resulted in PARP cleavage in MDA-MB-468 cells, although this effect was less intense compared to the effect of TiO\textsubscript{2} 100% anatase.

Bcl-2 family proteins play a crucial role in cell survival, since members of this family exert their effects regulating mitochondrial permeability.\textsuperscript{54,55} Several studies have pointed out the apoptotic effect of Evonik TiO\textsubscript{2} P25 on lymphocytes,\textsuperscript{46} reported time-dependent PARP cleavage induced by TiO\textsubscript{2} nanoparticles,\textsuperscript{57} and demonstrated increased expression of the proapoptotic protein Bax, which activated caspase-9 and caspase-3,\textsuperscript{31,34} following treatment of HeLa (human cervical adenocarcinoma) cells with TiO\textsubscript{2}.\textsuperscript{59} Moreover, Meena et al suggested that nano-TiO\textsubscript{2} induced oxidative stress and apoptosis occurred in a time- and dose-dependent manner.\textsuperscript{59} In addition, the activation of p53, Bax, caspase-3, and oxidative DNA damage was involved in the mechanistic pathways of nano-TiO\textsubscript{2} induced apoptosis in human embryonic kidney (HEK)-293 cells.\textsuperscript{60} According to our data, photoexcited TiO\textsubscript{2} 100% anatase and Evonik P25 nanoparticles increased the expression of proapoptotic Bax in MDA-MB-468 cells, thus establishing an apoptotic mechanism involving caspase-mediated PARP inactivation. In contrast, none of the dispersions of photoexcited TiO\textsubscript{2} nanoparticles affected Bax expression in MCF-7 cells.

The late stages of apoptosis are characterized by damage (fragmentation) of DNA. DNA destruction was reported in human embryonic kidney cells and lymphocytes treated with TiO\textsubscript{2} nanoparticles.\textsuperscript{59-61} We demonstrated that DNA damage indeed occurred specifically in the highly invasive MDA-MB-468 cells treated with photoexcited Sigma-Aldrich TiO\textsubscript{2} 100% anatase or Evonik TiO\textsubscript{2} P25.

Taken together, our results indicated that the mechanism of TiO\textsubscript{2} nanoparticles’ cytotoxicity involves increased Bax expression and caspase-mediated PARP cleavage, thus resulting in DNA fragmentation and cell apoptosis. As we have previously shown, small TiO\textsubscript{2} nanoparticles (2–3 nm) induced apoptosis specifically in MDA-MB-468 cells.\textsuperscript{8} Our data also demonstrated that the cytotoxicity of TiO\textsubscript{2} nanoparticles is cell type-dependent, since MCF-7 cells at concentrations up to 20 μM TiO\textsubscript{2} were less susceptible to TiO\textsubscript{2}-induced damage, compared to MDA-MB-468. These differences may be attributed to the different protein composition of the cell membrane affecting the manner that membrane proteins interact with TiO\textsubscript{2} particles.\textsuperscript{16,62,63}

The observed photocatalytic cell-killing effect of TiO\textsubscript{2} nanoparticles on human epithelial breast carcinoma MDA-MB-468 cells could possibly assist other means of cancer treatment. Since UVA irradiation is harmful for cells, chemical doping of TiO\textsubscript{2} nanoparticles with nonmetals (nitrogen, fluorine, sulfur, carbon), thus allowing activation using visible light or metals (silver), would eliminate the requirement for UVA irradiation. Then, doped TiO\textsubscript{2} nanoparticles could possibly be used as an anticancer regimen applied locally, followed by light irradiation focused on the tumor. Cancer cells can be selectively killed, as the light beam can be introduced via a fiber optic near a tumor region, where titanium oxide photocatalysts are also applied by simple injection.\textsuperscript{6}

**Conclusion**

The potential antitumor effects of photoactivated TiO\textsubscript{2} dispersions, nanostructured TiO\textsubscript{2} 100% anatase, and Evonik TiO\textsubscript{2} P25 in cultured MCF-7 and MDA-MB-468 breast cancer epithelial cells were examined. We documented that the cytotoxicity of TiO\textsubscript{2} nanoparticles of similar size but different crystal structure gradually decreased as their composition changed from pure anatase to anatase–rutile mixtures. We demonstrated that photoexcited TiO\textsubscript{2} in a pure anatase structure induced apoptosis specifically in MDA-MB-468 cells. Although the accurate molecular mechanism involved in the preferential death of highly malignant cancer cells awaits additional exploration, the obtained results indicate that the molecular mechanism of TiO\textsubscript{2} nanoparticle cytotoxicity involves increased proapoptotic Bax expression, caspase-mediated PARP cleavage, and DNA fragmentation, thus resulting in cell apoptosis.

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Disclosure
The authors report no conflicts of interest in this work.

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