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Photoelectrochemical Sensors for the Rapid Detection of DNA Damage Induced by Some Nanoparticles

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Abstract

Photoelectrochemcal sensors were developed for the rapid detection of oxidative DNA damage induced by titanium dioxide and polystyrene nanoparticles. Each sensor is a multilayer film prepared on a tin oxide nanoparticle electrode using layer- by-layer self assembly and is composed of separate layer of a photoelectrochemical indicator, DNA. The organic compound and heavy metals represent genotoxic chemicals leading two major damaging mechanisms, DNA adduct formation and DNA oxidation. The DNA damage is detected by monitoring the change of photocurrent of the indicator. In one sensor configuration, a DNA intercalator, $Ru(bpy)_2 (dppz)^{2+}$ [bpy=2, 2′ -bipyridine, dppz=dipyrido(3, 2-a: 2′ 3′-c) phenazine], was employed as the photoelectrochemical indicator. The damaged DNA on the sensor bound lesser $Ru(bpy)_2 (dppz)^{2+}$ than the intact DNA, resulting in a drop in photocurrent. In another configuration, ruthenium tris(bipyridine) was used as the indicator and was immobilized on the electrode underneath the DNA layer. After oxidative damage, the DNA bases became more accessible to photoelectrochemical oxidation than the intact DNA, producing a rise in photocurrent. Both sensors displayed substantial photocurrent change after incubation in titanium dioxide / polystyrene solution in a time – dependent manner. According to the data, damage of the DNA film was completed in 1h in titanium dioxide / polystyrene solution. In addition, the titanium dioxide induced much more sever damage than polysterene. The results were verified independently by gel electrophoresis and UV-Vis absorbance experiments. The photoelectrochemical reaction can be employed as a new and inexpensive screening tool for the rapid assessment of the genotoxicity of existing and new chemicals.

Keywords: Photoelectrochemical sensors; DNA damage; Nanoparticles.

Introduction

Nanoparticles are small enough to penetrate cell membranes and defenses, yet they are large enough to cause trouble by interfering with normal cell processes as replaced by the researchers at the University of Massachusetts. They examined the genotoxicity of silica, titanium dioxide, polystyrine and C60 fullerene nanoparticle suspensions using the alkaline single-cell gel electrophoresis assay (Comet assay) to quantify breaks in single and double stranded DNA. Such nanoparticles are currently in use in electronics, cosmetics, and chemical manufacturing, among others industries. Because of their extremely small size, they can be difficult to isolate from the large environment, as they are too small to be removed by conventional filtering techniques. Nanoparticles, engineered materials are about a billionth of a meter in size, could damage DNA and lead to cancer, according to research presented at the 2007 Annual Meeting of the American Association for Cancer Research [1].

Moreover, there roughly 100,000 chemicals available on the global market, 10,000 of them are hazardous, including about 200-300 confirmed carcinogenic agents [2]. In addition,

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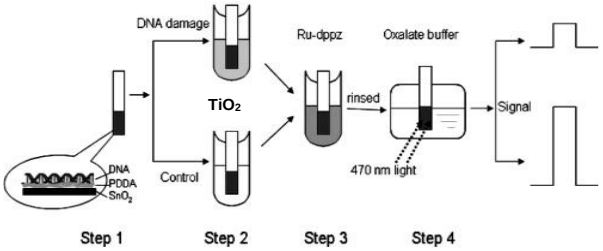
thousands of new chemicals are produced and utilized each year. Unfortunately, the vast majority of these chemicals do not have sufficient safety and health data, thus posing a great danger to human health and the ecosystem [2, 3]. Many chemicals have been found to possess carcinogenic toxicity. Some of these carcinogenic materials assert their toxic effect by causing damage in DNA, leading to gene mutation. In general, DNA damage is produced by one of the two major chemical routes, DNA oxidation by reactive oxygen species (ROS) and DNA adduct formation with exogenous chemicals and their *in vivo* metabolites [4,5]. According to the International Agency for Research on Cancer, Cr(VI), Ni(II), Ti(IV), Be, Cd, and As(III) compounds have been confirmed to be human carcinogens [6]. A number of studies have shown that metals induce their toxic effects primarily through their ability to produce ROS. Therefore, there is an urgent demand for rapid detection methods to screen the large number of existing and new chemicals for their genotoxicity.

There are currently a number of cell-based assays as well as biochemical and chemical analytical techniques for the detection of DNA damage and the assessment of genetic toxicity. DNA damage products have been identified and quantified by a wide range of analytical techniques, such as single-cell gel electrophoresis, ^{32}P- postlabeling, immunoassay, gas chromatography/mass spectrometry, high performance liquid chromatography, and electrochemical and electrochemiluminescence sensors [7-9]. As a detection method, photoelectrochemistry is well suited for the rapid and high-throughput screening of genotoxic chemicals [10]. The photoelectrochemistry-based analytical method is potentially very sensitive, as the excitation source(light) is different from the detection signal(current). In addition, the instrument should be simpler and of lower cost than all the optical detection methods due to the use of electronic detection, particularly in an array format. It compares favorably with the optical detection methods such as fluorescence, chemiluminescence, and electrochemilum-inescence, which have to use complex and expensive optical imaging devices and sophisticated image- recognition software. Over the years, photoelectrochemistry-based analytical methods have been employed in the quantification of DNA[11] and DNA hybridization[12]. Recently, we reported a photoelectrochemical sensor for the detection of DNA damage by Fe^{2+} and styrene oxide[13]. The sensor was assembled by depositing a layer of calf-thymus DNA on a tin oxide nanoparticle electrode. A DNA intercalator, $Ru(bpy)_2$ $(dppz)^{2+}$ [bpy=2, 2′ -bipyridine, dppz=dipyrido(3, 2-a: 2′ 3′-c) phenazine], was employed as the photoelectrochemical signal reporter. When the sensor was exposed to a solution containing 10µM TiO_2 or 10 µM polystyrene nanoparticle , the DNA on the sensor surface was damaged by the nanoparticles, resulting in less binding with $Ru(bpy)_2$ $(dppz)^{2+}$ and consequently lower signal than the native DNA (**Scheme 1**).



Scheme 1. **Illustration of Experimental Procedure: (1) Preparation of DNA film electrode, (2) DNA damage reaction, (3) Binding of signal molecule, and (4) Photocurrent measurement**

Tin oxide nanoparticle electrode was prepared by the alternate layer-by –layer electrostatic self assembly approach with poly(diallyldimethyl ammonium chloride)(PDDA) and ds-DNA solution was immobilized on it, which was exposed by titanium dioxide/ polystyrene (as damaging agent) for 1h at 37ºC and rotation 200 rpm then DNA was damaged. A DNA intercalator $Ru(bpy)_2$ $(dppz)^{2+}$, was employed as the photoelectrochemical signal reporter. The photocurrent was produced by the conversion of Ru^{2+*} to Ru^{3+}. Thermodynamically, Ru^{3+} can oxidize guanine and adenine bases in DNA in the presence of oxalate buffer and get reduced back to Ru^{2+} resulting in the recycling of metal complex an enhance the photocurrent. The photocurrent was measured on a CHIA electrochemical analyzer using Pt flag counter electrode, and Ag/AgCl reference electrode at 473 nm blue laser light.

Experimental

Reagents and solutions

Poly-(diallyldimethyl ammonium chloride) (PDDA) and single and double-stranded calf thymus DNA (ss-DNA and ds-DNA, 13K base pairs), were purchased from Sigma-Aldrich(St. Louis, MO,USA). Titanium dioxide nanoparticles (99.9% purity referred to as TiO_2 40nm) and polystyrene oxide nanoparticles (99.5% purity) were also purchased from Sigma-Aldrich (St. Louis, MO, USA). Fifteen percent tin(IV) oxide, as a colloidal dispersion of 15 nm particles, was obtained from Alfa Aesar (Ward Hill, MA), and so was hydrogen peroxide. All other chemicals and solvents were of analytical grade. $Ru\text{-}(bpy)_2\ (dppz)\ (BF_4)_2$ was synthesized according to the published procedure [14, 15]. All solutions were prepared in high – purity water from a Millipore Milli-Q (Biocel water purification system). Tin-doped indium oxide conductive glass was supplied by Weiguang Corp.(Shenzhen, People's Republic of China).

Titanium dioxide nanoparticle standard solution (1000 mg L^{-1})

A 100-mL stock solution (1mg mL^{-1}) was prepared by dissolving titanium dioxide (TiO_2 40nm, purity 99.9%) in 500 µL of 32% H_2O_2 and 300 µL of 1% w/v Na_2CO_3 solutions following the published procedure [16, 16a]. The volume was made up to the mark with Milli Q water. The resulting solution was ultrasonicated for half an hour until transparent clear aqueous solution was obtained. Electron microscopy studies revealed that the actual size of titanium nanoparticle was 2-5 nm.

Polystyrene nanoparticle standard solution (1000 mg L^{-1})

A 100-mL stock solution (1mg mL^{-1}) was prepared by dissolving polystyrene (polystyrene 100nm, purity 99%). A 100mg portion was placed in a 15 mL centrifuge tube fitted with a glass stopper, and 10-mL of diethylbenzene was added. The flask was stoppered and placed in an Eberbanch horizontal shaker. The mixture agitated until all polymer had dissolved (within 1hr) following the published procedure [17], and the solvent evaporated thoroughly under vacuum. The residue was redissolved in 10 mL of 10% Triton X-100 solution and diluted to 100-mL with highly purified water and the aqueous solution thus obtained was sonicated (1/2 hr) to produce a clear solution. Electron microscopy studies revealed that the actual size of polystyrene nanoparticle was 5-7 nm.

Film assembly

SnO_2 nanoparticle electrodes were prepared by following the previous method [18, 19] (**Scheme 1**). The concentrations of PDDA and DNA solutions for film deposition were 2 and 0.5 $mgmL^{-1}$, respectively. The DNA – modified electrode was denoted as SnO_2 / PDDA / DNA. The DNA film on the electrode was damaged by exposing to TiO_2 / polystyrene solution at 37 ^0C with vortex (200rpm) for 1h for a time period as specified. Then the electrode was taken out and rinsed with water.

Photoelectrochemical measurement

The photocurrent was measured on a CHI 630A electrochemical analyzer (Austin, TX) using a Pt flag counter electrode, Ag / AgCl (3M KCl) reference electrode, and a bias voltage of +0.1V. The area of the working electrode in contact with the electrolyte was 0.25 cm^2. The light source of photocurrent measurement was a 473 nm blue laser with 1.5 mW/cm^2 power and an illumination area of 0.18 cm^2. The light source for action spectrum measurement was a 500W xenon lamp with a light intensity of 0.168 mW/cm^2. For SnO_2 / PDDA / TiO_2 / ds-DNA sensor, after DNA damage reaction and washing, the electrode was further reacted with 50 µM $Ru(bpy)_2\ (dppz)^{2+}$ for 30 min for the intercalation to take place. After the reaction the unbound metal complex was washed off by water. Photocurrent was then measured by placing the electrode in 20 mM oxalate buffer pH 5.8.

Gel electrophoresis

The damaged ds-DNA sample for gel electrophoresis was prepared by the incubation of 0.1 mg mL^{-1} ds-DNA, 10 mM H_2O_2 5 mM Na_2CO_3 and 100 mg L^{-1} (2, 1 and 0.5 mgL^{-1} final concentrations) TiO_2 or polystyrene at 37 ^0C with

vortex (200 rmp) for 1 and 1.5 h, respectively. The incubated DNA sample was then electrophoresed on a 1.2% agarose gel in 0.5 ×TBE (45 mM Tris, 45 mM boric acid, 1 mM EDTA, pH 8.0) and 0.5 μg mL^{-1} ethidium bromide for 30 min at 7.5 V / cm.

UV / Vis absorption measurment

The absorbance intensity was measured on a DU 800 double-beam UV – Vis spectrophotometer using 250 nm. A solution containing 5 μg mL^{-1} intact or damaged ds-DNA in 20 mM phosphate buffer pH 7.3 and various concentrations of $Ru(bpy)_2(dppz)^{2+}$ in each well was shaken for 2 min before the measurement. The light intensity from a well containing the buffer alone was used for background(blank) subtraction. The effect of 10 mM H_2O_2 and 5 mM Na_2CO_3 solutions on DNA damage was also studied. The damaged ds-DNA sample for absorbance measurement was obtained by reacting with 2, 1 and 0.5 mg L^{-1} TiO_2 or polystyrene at at 37 ^{0}C with vortex (200 rmp) for 1 and 1.5 h, respectively.

Results and Discussion

Detection methods

Here we present two photoelectrochemical methods to detect DNA damage. One is based on photoelectrochemically catalyzed base oxidation, and the other employs a photoelectrochemical indicator (Scheme 1).

In the first method, a ruthenium tris(bipyridine)-labeled avidin film and a ds-DNA film were assembled successively on a tin oxide nanoparticle film electrode. Photocurrent enhancement requires regeneration of the ground state Ru^{2+} complex by a reducing agent. By analogy with previously proposed mechanisms for electrocatalytic oxidation of DNA, [20, 21] the photoelectro- chemical oxidation reaction in the current system could be represented as in Scheme 2. Initial excitation of Ru^{2+} after absorbing photon energy gives Ru^{2+}* (eq 1). Ru^{2+}* injects an electron into the semiconductor (SnO_2) and produces Ru^{3+} (eq 2), which is then reduced back to Ru^{2+} (eq 3) by guanine and adenine bases in DNA, resulting in the recycling of the metal complex and enhanced photocurrent. Because the oxidation potential of Ru^{2+}*/1+ (0.78 V) is much lower than that of guanine and adenine [10], the excited state does not oxidize the DNA bases directly.

Scheme 2. Proposed mechanisms of photoelectrochemical oxidation of DNA by $Ru(bpy)_3^{2+}$

$Ru^{2+} + h\upsilon \rightarrow Ru^{2+*}$ ----------(1)

$Ru^{2+*} \rightarrow Ru^{3+} + e$ ----------(2)

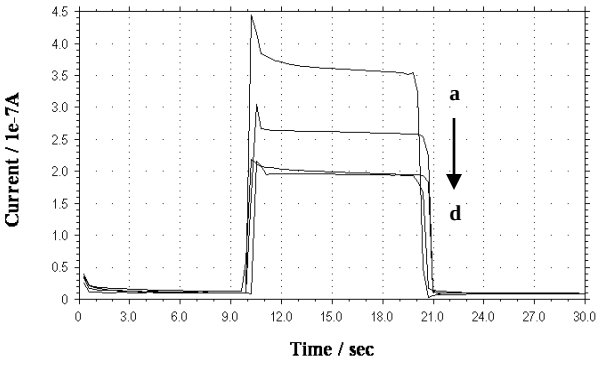
$Ru^{3+} + G \text{ (or A)} \rightarrow Ru^{2+} + G_{ox}(\text{ or } A_{ox})$ ----(3)

In the second method, an unlabeled avidin film and a ds-DNA film were assembled on the semiconductor electrode. A DNA intercalator, $Ru(bpy)_2(dppz)^{2+}$, was employed as the photoelectronchemical signal reporter. The metal complex binds to the ds-DNA film by inserting its dppz ligand into the space between adjacent base pairs with high affinity (binding constant $K = 10^6$-10^7 M^{-1}) and selectivity [22]. A steady-state photocurrent was measured in an oxalate buffer which serves as the electron donor to recycle the indicator. After damage, less $Ru(bpy)_2(dppz)^{2+}$ binds to the DNA film due to the reduced binding sites, and results in a drop in photocurrent.

Detection of DNA damaged by polystyrene nanoparticle

Polystyrene is used extensively in the chemical industry and is classified as a carcinogen. In vivo, polystyrene is metabolized by liver enzymes such as cytochrome P450 into styrene 7, 8-oxide, a much more potent carcinogen [23]. The polystyrene reacts in vitro with guanine and adenine nucleotides to form a variety of adducts, leading to DNA damage. Many other genotoxic organic chemicals follow a similar mechanistic pathway, i.e., from enzyme activation to adduct formation to DNA damage [24]. Therefore, a rapid method for the detection of DNA adducts is valuable to screen organic chemicals for their potential genotoxicity. DNA damage induced by polystyrene nanoparticle was first detected by the photoelectrochemically catalyzed base oxidation method. The avidin-Ru / ds-DNA multilayer film was assembled on the SnO_2 electrode as described above. The electrode was incubated in 2, 1, 0.5 mg L^{-1} polystyrene at 37 °C for the time required. After the reaction, photocurrent was measured in a

phosphate buffer. (Fig. 1) shows the photocurrent response for different period of incubation time. The current increased with incubation time and reached its maximum after 1.5 h, at which time the reaction was presumably completed. In the absence of polystyrene, the photocurrent was essentially unchanged, proving the increase was caused by polystyrene nanoparticle. One of the major DNA adducts is with the 2-NH_2 group of guanine, and involved in the hydrogen bonding interaction with cytosine. Adduct formation disrupts the base-paring interaction and changes the local DNA structure, thus exposing more bases for photoelectrochemical oxidation. When the damage was complete, the photocurrent was about 2 times higher than that of the control. In a previous report, DNA films damaged by styrene oxide were detected by catalytic voltammetry [25]. The chemical reaction was found to be complete within 30 min, accompanied by a 60% increase in the oxidation current. Our results indicate the photoelectrochemical method is much more sensitive than catalytic voltammetry. The absolute sensitivity of the photoelectrochemical method cannot be assessed at present due to the lack of information about the amount of damaged DNA in the film, which will be estimated in future work by established methods. Polystyrene -induced DNA damage was also monitored using the $Ru(bpy)_2(dppz)^{2+}$ intercalator. The avidin/ds-DNA film on SnO_2 was treated in polystyrene nanpaticle, reacted with the intercalator, and then measured in 30 mM oxalate buffer. Figure 1 shows the photocurrent response as a function of the reaction time in polystyrene nanoparticle. Because the number of intercalation sites in the damaged DNA is less than that in the intact DNA, the photocurrent is reduced. Similar to the results obtained in the base oxidation measurement, the current decreased progressively with the reaction time and stabilized after 2h(when adjusted for the control). The control also showed gradual loss of signal over the time the DNA film was immersed in the phosphate buffer, probably due to slight de-sorption of some DNA molecules in the film. The de-sorption was also observed in (Fig. 1). The small change in the photoelectrochemical response of the indicator after polystyrene nanoparticle reaction is consistent with the structural information.



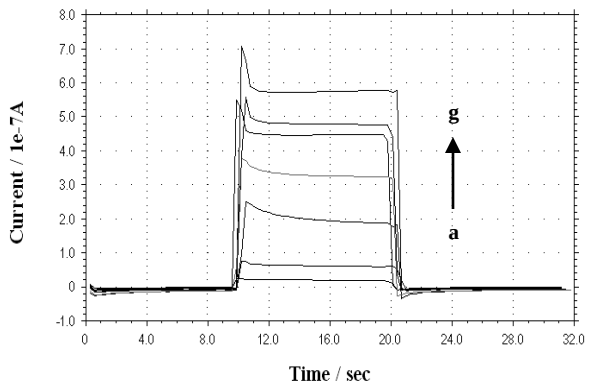
SnO_2 / PDDA / DNA

Figure 1. **Anodic photocurrent response of $Ru(bpy)_2(dppz)^{2+}$ bound to SnO_2 / PDDA /ds- DNA electrode after the DNA film was exposed to a: 2 mg mL^{-1} psnp, b: 1 mg mL^{-1} psnp, c: 0.5 mg mL^{-1} psnp and d: phosphate buffer.**

Detection of DNA damaged by the titanium dioxide nanoparticle

Among the environmentally polluted metal compounds, Cr(VI), Ni(II), Cd, Ti(IV) and As(III) have been confirmed to be carcinogenic to human beings. Cobalt(II) and iron(III) nitrilotriacetate are suspected human carcinogens. These compounds assert their carcinogenic effect either by inducing DNA damage or by inhibiting DNA repair processes [26]. One of the frequently investigated routes of DNA damage is through metal catalyzed generation of reactive oxygen species such as hydroxyl free radical in the presence of H_2O_2, the so-called Fenton reaction. In vitro the Fenton reaction causes DNA cleavage at almost every nucleotide site, leading to base loss, chain breakage, and base oxidation [27]. Many of the base oxidation products are also oxidizable, the most cited of which is 8-oxo-7,8-dihydro-2¢-deoxyguanosine (8-oxo-dG). The TiO_2 nanopa-rticles were studied in our work as a model for metal-induced oxidative DNA damage. The damage was first investigated by the base oxidation detection method described above. In the experiment, the SnO_2 / PDDA / DNA sensor was assembled as usual and then exposed to 1, 0.5 and 0.1 mg L^{-1} Ti^{4+} for the required time. Finally, the DNA film was allowed to bind to $Ru(bpy)_2(dppz)^{2+}$. The photocurrent was then measured in a phosphate buffer. Figure 2 shows the photocurrent change as a function of the reaction time, from which it is obvious that the

damage process proceeded at a much faster rate than polystyrene nanparticle adduct formation and was completed in 1h. As can be seen in Figure 2, the measured signal was reduced by one – third as compared with the blank control (buffer only) and also reduced than H_2O_2 control (H_2O_2 only), Na_2CO_3 control (Na_2CO_3 only) and mixture of H_2O_2 + Na_2CO_3 control (H_2O_2 + Na_2CO_3 only).As can be seen in Figure 2, there is no any effect of H_2O_2, Na_2CO_3 and mixture of H_2O_2 and Na_2CO_3 on the DNA damage response. Incubation in either H_2O_2 or Na_2CO_3 or mixture of H_2O_2 + Na_2CO_3 alone did not have any appreciable effect on the response. After 1 h in the TiO_2 reagents, the current decreased with increase of Ti^{4+} concentration. It was observed that DNA was totally damaged with high concentration ($1mgL^{-1}$) of TiO_2 nanoparticle. DNA damaging tendency was decreased with decreasing concentration of TiO_2 which is shown in Fig. 2. The maximum photocurrent was observed for phosphate buffer which was in good agreement with theoretical concept.



SnO_2 / PDDA / DNA

Figure 2. **Anodic photocurrent response of $Ru(bpy)_2(dppz)^{2+}$ bound to SnO_2 / PDDA / ds- DNA electrode after the DNA film was exposed to a: 1 mg mL^{-1} of TiO_2, b: 0.5 mg mL^{-1} of TiO_2, c: 0.1 mg mL^{-1} of TiO_2, d: 100µM Na_2CO_3, e: 50µM Na_2CO_3+2.5M H_2O_2 f: 5 M H_2O_2 and g: 20 mM sodium phosphate buffer (pH 7.3).**

The final signal is more than 3 times higher than that of the reaction with polystyrene nanoparticle, see (Fig. 1 & 2) suggesting that the metal induced DNA damage is much more severe than that induced by the organic compound. Detection of the TiO_2-damaged DNA film with the ruthenium intercalator produced results consistent with those of the base oxidation method. The photocurrent dropped immediately after the reaction and became steady after 1 h, at which time the response was only about 15% of the original signal. The concentration of TiO_2 used in the work is most likely higher than the concentration found in vivo. To validate our findings in the in vivo situation, a concentration range covering the nanogram regime will be investigated.

Verification of the results by gel electrophoresis and UV-Visible absorbance experiments

The results were verified independently by gel electrophoresis and UV-Visible absorbance experiments. Agarose gel electrophoresis of the DNA incubated with polystyrene and titanium dioxide nanoparticles. It was clearly found that DNA was totally damaged with increase of polystyrene nanoparticle concentration (Fig. 3). It was also found that DNA was totally damaged by higher concentration of titanium dioxide nanoparticle concentration (Fig. 4). The maximum brightness was observed for control buffer. The damaging tendency is gradually decrease with decreasing the concentration of polystyrene or TiO_2 nanoparticles, respectively (Fig. 3 & 4). It can be seen from (Fig. 4) that there is no appreciable effect of H_2O_2, Na_2CO_3 or mixture of H_2O_2 + Na_2CO_3 on DNA damage. So the results obtained by our photoelectrochemical method were in good agreement with those obtained by agarose gel electrophoresis.

The results were also verified by UV-Visible spectrophotometry. It was found that DNA was damaged by polystyrene except water which gave DNA spectra at 255nm. The results are shown in (Fig. 5). It can be seen from (Fig. 6), that DNA was totally damaged by different concentration of TiO_2 nanoparticle, except only Na_2CO_3 and phosphate buffer which gave DNA peaks at 255 nm. Since H_2O_2 absorbs UV light and gives high absorbance so all the solutions which contains H_2O_2 gave high UV absorption spectrums. The results are shown in (Fig. 6). So the results obtained by our photoelectrochemical method were in good agreement with those obtained by UV – Visible absorbance measurements. It can be found from both the experiments that DNA was more severely damaged by TiO_2 nanoparticle than polysterene.

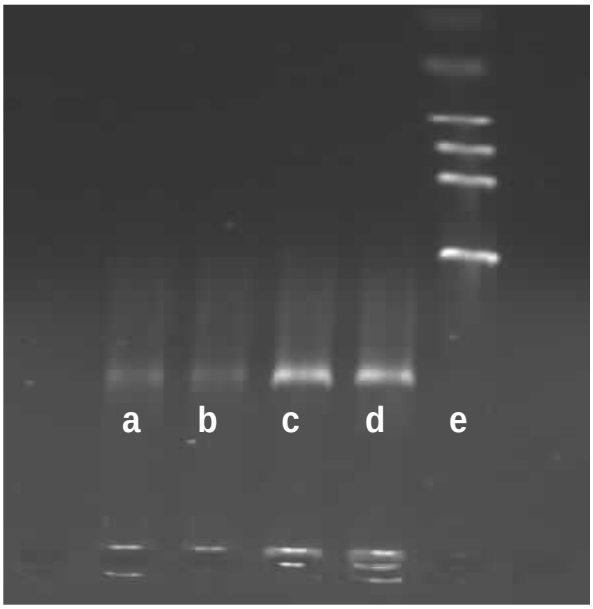


Figure 3. **Agarose gel electrophoresis of the DNA incubated with psnp.**

a: 2mg mL^{-1}psnp, b : 1mg mL^{-1}psnp,
c : 0.5mg mL^{-1}psnp, d: phosphate buffer and
e : Marker

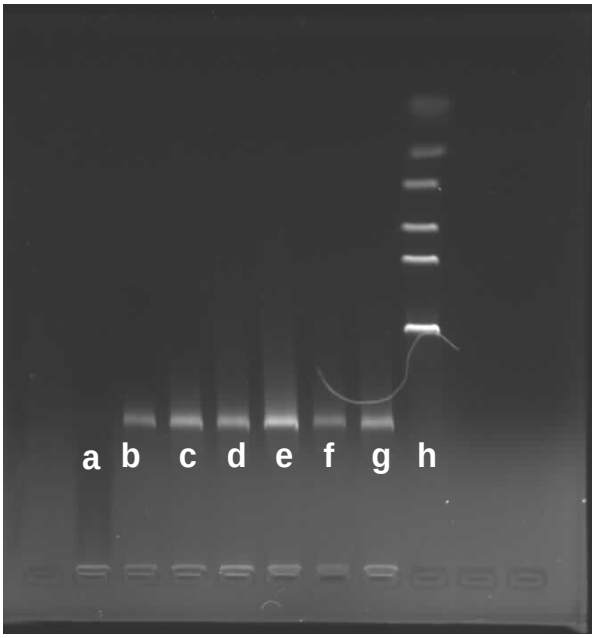


Figure 4. **Agarose gel electrophoresis of the DNA incubated with TiO_2**

a: 1 mg mL^{-1} of TiO_2, b: 0.5 mg mL^{-1} of TiO_2,
c: 0.1 mg mL^{-1} of TiO_2, d: 100µM Na_2CO_3,
e: 5 M H_2O_2, f: 50µM Na_2CO_3+2.5M H_2O_2,
g: 20 mM sodium phosphate buffer (pH 7.3)
h: Marker

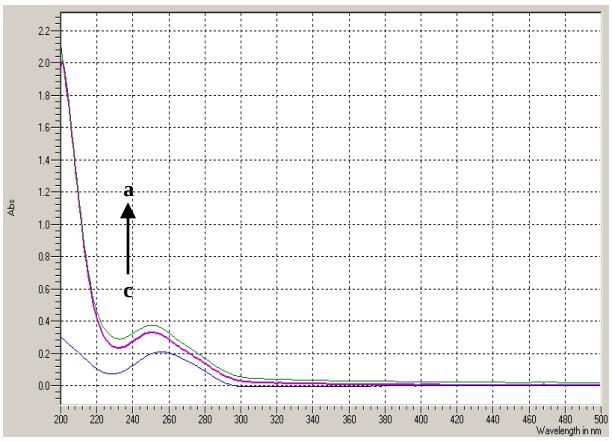


Figure 5. **UV-Vis absorption spectrum of the DNA incubated with psnp solution.**

a: 1mg mL^{-1} psnp, b: 0.5mg mL^{-1} psnp and c: blank (water)

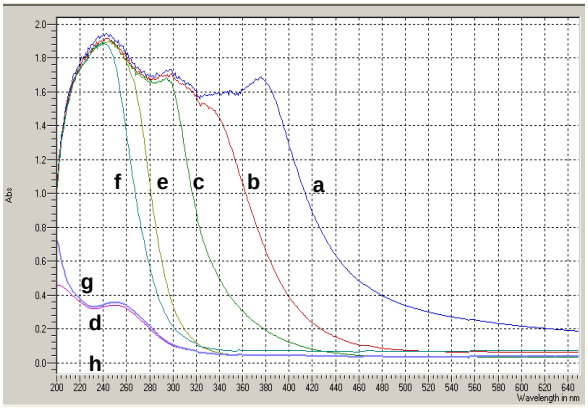


Figure 6. **UV-Vis absorption spectrum of the DNA incubated with TiO_2 solution.**

a: 1 mg mL^{-1} of TiO_2, b: 0.5 mg mL^{-1} of TiO_2,
c: 0.1 mg mL^{-1} of TiO_2, d: 100µM Na_2CO_3,
e: 5 M H_2O_2 f: 50µM Na_2CO_3+2.5M H_2O_2,
g: 20mM phosphate Buffer (pH 7.3) and
h: Blank (Water)

Conclusions

This is a rapid, highly sensitive and inexpensive technique for the detection of DNA damage and a powerful tool for the large-scale screening of chemical genotoxicity.

This is the first time titanium dioxide was completely dissolved in water using nontoxic H_2O_2 and Na_2CO_3 without strong acid or carcinogenic organic solvents.

The titanium dioxide nanoparticle induced much more sever damage than polystyrene. The detection apparatus is inexpensive and is made of some common electronics and a low –power laser light as compared to other large instruments (e. g. spectrofluorometer, LC-MS etc).

The developed DNA sensor (induced by tianium dioxide nanoparticle or polystyrene nanoparticle) has the potential to become a powerful tool for the rapid, low cost and large – scale screening of chemical genotoxicity.

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