RESEARCH ARTICLE

Histopathological Analysis and Renal Toxicity of Silver Nanoparticles upon Frequent Oral Exposure in Wistar Rats

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Abstract

Silver Nanoparticles (AgNPs) are the most widely produced engineered nanoparticles and account for more than 50% of global nanomaterial consumer products. Because of their small size, AgNPs can enter the human body through ingestion, inhalation, and skin contact. Kidneys, lungs, nervous system, and liver are organs prone to the accumulation of AgNPs and cause various histological changes as well as damage to organs. The objective of this study was to evaluate the renal toxicity induced by AgNPs after repeated oral exposure through pathomorphology and immunohistochemistry of kidneys in Wistar rats. Wistar rats (n=35) of either sex were randomly classified into two groups (treated, n=20; and control group, n=15). The control group of rats received normal feed and water, while test rats were given AgNPs in the form of suspension by oral gavaging at NOAEL dose (30 mg/kg b.wt.). On day 0, 5 rats from test group were weighed and euthanized, while at days 30th, 60th and 90th of the experiment, 5 rats from each control and test group were weighed and humanely euthanized to check pathomorphological changes of kidney. Histopathological changes were assessed using hematoxylin-eosin (H&E) stain. For immunohistochemistry, at day 90th kidney tissue sections of treated rats were examined for the presence of antigen-antibody complexes using immunoperoxidase reaction to check histopathological changes. Pathomorphological studies revealed gross changes after 90 days of AgNPs exposure as compared to control group. Congestion and endothelial swelling in glomerular capillaries, focal infiltration of inflammatory cells in the glomeruli and in medullary area, cloudy swelling of the kidney tubular epithelium (KTE) which later progressed to coagulative necrosis were seen. Apoptotic figures like blebs were seen in the renal tubules. Proliferation of mesangial cells and expansion of mesangial matrix was seen at 60th and 90th day of experiment**.** Thus, AgNPs were responsible for *in vivo* renal damage.

Key words: Immunohistochemistry, Histopathology, Renal toxicity, Silver nanoparticles, Wistar rat.

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Introduction

Nanoparticles and structures have been used by humans since time immemorial. Currently, silver nanoparticles (AgNPs) are one of the most popular materials explored by nanotechnology-derived nanostructures (Saravanan *et al*., 2018). Sir Walter Scott, in his book *Talisman*, also mentioned Damascus steel as having a curved narrow blade of dull blue colour, which was marked with 10 million of meandering lines that was made in India and called as Wootz steel (Srinivasan, 2007). During the 9th to 7th centuries, silver or copper containing glittering ceramic glazes were used in the Islamic world, and later in Europe, which contains metals in the nanoscale range (Pradell *et al*., 2007). AgNPs are widely used in the food industry in packaging and storage to increase the shelf life and quality of food (Gaillet and Rouanet, 2015). Industrial effluents result in accumulation of AgNPs in aquatic ecosystem through biomagnification (Gambardella *et al*., 2015). Recent studies have also demonstrated that AgNPs incorporated in food packaging can migrate from packaging into food under several usage conditions (Mackevica *et al.,* 2016; Choi *et al.,* 2018). Thus, the important sources of oral exposure can be the presence of AgNPs in dietary supplements, water contamination, or food fish and other aquatic organisms (Gaillet and Rouanet, 2015).

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AgNPs are engineered nanoparticles in themselves because they don't occur naturally and are used for synthesis of other engineered nanomaterial (ENMs). They account for more than 50% of global nanomaterial consumer products. Because of their small size, AgNPs can enter the human body through ingestion, inhalation, and skin contact (Crosera *et al*., 2009). Kidneys, lungs, nervous system, and liver are organs prone to the accumulation of AgNPs. The most well-known mechanism of AgNPs cytotoxicity involves the induction of oxidative stress and changes in different organs (Chairuangkitti *et al*., 2013). Studies conducted both *in vitro* and *in vivo* have demonstrated AgNPs induction of cytotoxicity and inflammatory effects in many cells and tissues (Nosrati *et al*., 2021). One common characteristic of renal diseases, which can have several aetiologies, including toxins, is decreased renal function brought on by intrinsic renal cell populations undergoing apoptosis. Increased level of apoptosis can lead to glomerulosclerosis and tubular atrophy (Schelling, 2016). The main objective of the current study was to evaluate the renal toxicity induced by AgNPs after repeated oral exposure through pathomorphology and immunohistochemistry of kidneys in Wistar rats.

Materials and Methods

Experimental Animal and Design

Following approval of Institutional Animal Ethics Committee of College of Veterinary Sciences, GBPUAT, Pantnagar (India) (No. IAEC/CVASc/VPP/419 dated 12-12-2020), adult Wistar rats (n=35) of either sex were used as experimental animals during the research work and kept in controlled environment with required food and water. Out of total 35 experimental laboratory animals two random groups were made, *i.e.,* control and test groups containing 15 and 20 rats, respectively. All the rats were immunized with 0.1 mL of Ranikhet disease vaccine having R_2B strain at day 0 of the experiment. The control group of rats received normal feed and water, while test rats were given AgNPs in the form of water suspension by oral gavaging at no observed adverse effect level (NOAEL) dose (30 mg/kg b.wt.) for 90 days (Kim *et al*., 2010). The AgNPs (less than 90 nm, concentration 12 mg/mL) used in the present study were purchased from the Sisco Research Laboratories, Pvt. Ltd., India. Five rats of test group were weighed and sacrificed in a humane way on day 0 of experiment, whereas 5 rats from each control and test group were weighed and sacrificed in a humane way on days 30^{th}, 60^{th} and 90^{th} to assess kidney damage and toxicity through assessment of various parameters.

Apoptosis Determination

To determine apoptosis, quantification of DNA fragmentation in kidney tissues was done according to the standard protocol (Attia *et al*., 2018). 150 µL of the coloured solution developed was transferred to wells of a 96-well microplate and OD was read at 600 nm.

Macro- and Microscopic Pathology

Standard necropsy procedures were followed on all euthanized rats (Sengupta *et al*., 2016) to check the presence of gross lesions in kidneys. Kidney, ureter and urinary bladder were collected in 10% buffered formalin and standard histopathological procedures were followed (Culling, 2013). Staining was done with haematoxylin and eosin (H&E) stain and PAS staining was done at 90^{th} day for detailed observations (Singh and Chauhan, 2008). After completion of the procedure tissues were examined for the microscopic changes under the light microscope.

Immunohistochemistry

Day 90^{th} kidney tissue sections of treated rats were tested for the presence of antigen-antibody complexes using immunoperoxidase reaction. The paraffin embedded tissue sections of 4-5 µm thickness were processed using standard histopathological and immunohistochemical procedures as described by Joshi and Chauhan (2012). The processed slides were then visualized under light microscope and were interpreted.

Results and Discussion

The present study was done to determine pathological effects of oral exposure of silver nanoparticles in Wistar rats at NOAEL dose for a period of 90 days. The observations made in the present study were with respect to pathomorphological alterations including gross and histopathological changes.

Patho-Morphological Changes

Gross changes: No statistically significant lesions were seen in control group. In AgNPs treated rats, at 90^{th} day of treatment the kidney was enlarged and pale as compared to control rats and at 30^{th} and 60^{th} days of the experiment no significant gross changes were observed. Gross lesions are described in Table 1.

Apoptosis in kidney tissues: Mean apoptosis values of all the rats used in the experiment were expressed as % DNA fragmentation. Mean apoptosis values in group I rats were 6.66 ± 0.14, 6.82 ± 0.33, 8.56 ± 0.19 and 9.06 ± 0.17 % DNA fragmentation at 0, 30^{th}, 60^{th} and 90^{th} day post-treatment (DPT), respectively. In group II rats, the respective mean apoptosis values were 6.66±0.14, 12.34±0.19, 18.45±0.19 and 24.18±0.18 % DNA fragmentation. There was significant increase ($p<0.05$) in mean apoptosis values in AgNPs treated rats at 30^{th}, 60^{th} and 90^{th} DPT as compared to control rats. The increase in apoptosis values in treatment group was by

Table 1: Severity of lesions at different time intervals in AgNPs treated rats

LESIONS	30th DPT	60th DPT	90th DPT
Congestion of glomerular capillaries	+	++	+++
Thickening of glomerular basement membrane leading to tram truck appearance and hyperlobulation	-	+	++
Increase in mesangial cells and matrix	+	++	+++
Thickening of the glomerular basement membrane	-	+	++
Damage to bowman's capsule	-	+	++
Interstitial haemorrhage	+	++	+++
Coagulative necrosis of the tubular epithelial cells	+	++	+++
Apoptotic figures like blebs	-	+	++

'- sign' = absence of lesions; '+ sign', '++ sign',' +++ sign' indicate the presence of lesion with increase in severity with '+++' showing highest severity followed by '++' and '+' respectively. DPT = Days post-therapy.

80.94%, 115.54% and 166.89% at 30th, 60th and 90th DPT, in AgNPs treated rats as compared to control rats.

Present study revealed that apoptosis values were increased significantly in renal tissues of treated rats at 30th, 60th and 90th DPT as compared to control rats which conclude toxic effect of AgNPs in kidney. High degree of apoptosis was observed when AgNPs were administered intraperitoneally at 80 mg/kg/b.wt. for 4 weeks (Albrahim, 2020). Similar results were obtained in renal cell line HEK293T (Mao *et al.,* 2018) and kidney tissues after administration of AgNPs (Tiwari *et al*., 2011). AgNPs bind with the cell surface and can pass through the cell membrane, this binding changes the cell signalling pathway and the maturation of cells (Gopinath *et al.,* 2017), and lead to apoptosis. Also increased ROS level enhances H_2O_2 level which can cause damage to cellular components and results in injury to DNA strands, chromosome aberration, and conformational changes in proteins.

Histopathological Changes in Kidneys

No statistically significant lesions were obtained in control group whereas in AgNPs treated rats, lesions of cell injury were obtained at 30th, 60th and 90th day of the study. At 30th day cortical area showed congestion and endothelial swelling in glomerular capillaries, focal infiltration of inflammatory cells in the glomeruli, narrowing of Bowman's spaces, glomeruli looked like more collapsed and capillary lumen seemed to be reduced. In medullary area, cloudy swelling and later coagulative necrosis were seen in the tubular cells along with mild interstitial haemorrhages. At 60th day changes include in cortical area are severe congestion of glomerular capillaries and endothelial swelling was seen at some regions, focal infiltration of inflammatory cells in the glomeruli, narrowing of Bowman's spaces with synechia (tip lesions) at some places, increase in size of bowman's capsule along with increase in mesangial cellularity (Fig. 1) thickening of the glomerular basement membrane were observed when compared with control group. Medullary area showing coagulative necrosis was seen in many of the epithelial cells of tubules. Also, apoptotic figures like- blebs were seen in the renal tubules. Widespread interstitial haemorrhages were seen. At 90th day cortical area showed severe congestion of glomerular capillaries with increased cellularity, endothelial swelling, infiltration of inflammatory cells in the glomeruli, narrowing of Bowman's spaces and architectural deformities of the Bowman's capsule were prominent. Swelling and damage was observed in the parietal squamous epithelial layer of Bowman's capsule at many places. Medullary area includes coagulative necrosis was seen in many of the KTE cells of many tubules. Apoptotic figures like blebs were seen in the renal tubules. Widespread interstitial haemorrhages were seen (Fig. 2, 3, 4). PAS staining revealed thickening of the glomerular basement membrane giving tram –track appearance or hyperlobulated appearance at 90th day (Fig. 5).

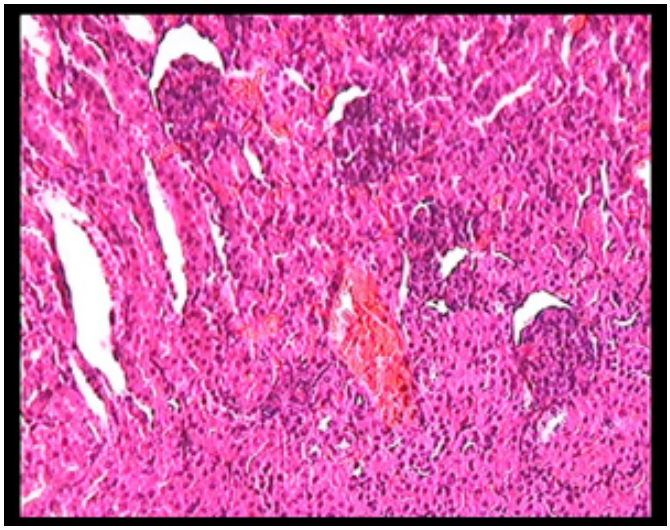


Fig. 1: Photomicrograph of kidney showing increase in mesangial cells and mesangial matrix, narrowing of Bowman's spaces and congestion of arterioles (90 DPT, Group II treated rats, H&E X 100).

Gross and Microscopic lessons observed in the present study were similar to the results obtained after intraperitoneal administration of AgNPs at 4 g/kg for 4 weeks (Zamil, 2018). At day 60th and 90th severe degeneration and necrosis of tubular epithelial cells along with apoptosis seen was in agreement with that obtained after intraperitoneal administration of AgNPs at 50 mg/kg b.wt for 14 days (Hassanen *et al*., 2019). These results

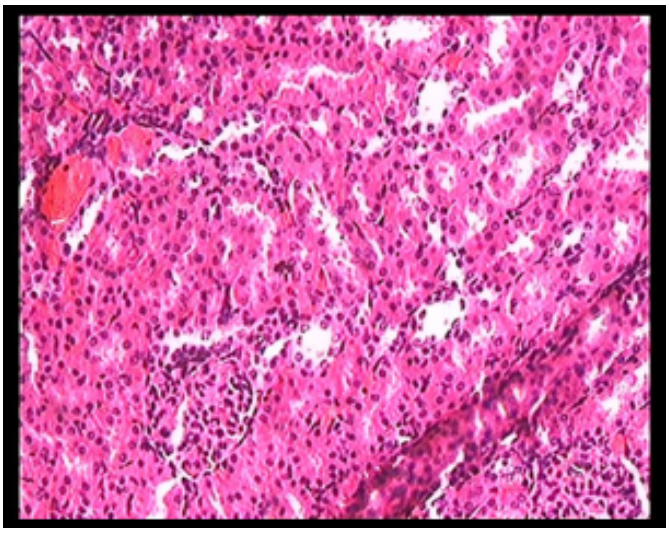


Fig. 2: Photomicrograph of kidney tissues showing expanded glomerulus with proliferating tuft cells and infiltration of inflammatory cells (60 DPT, Group II treated rats, H&E X100).

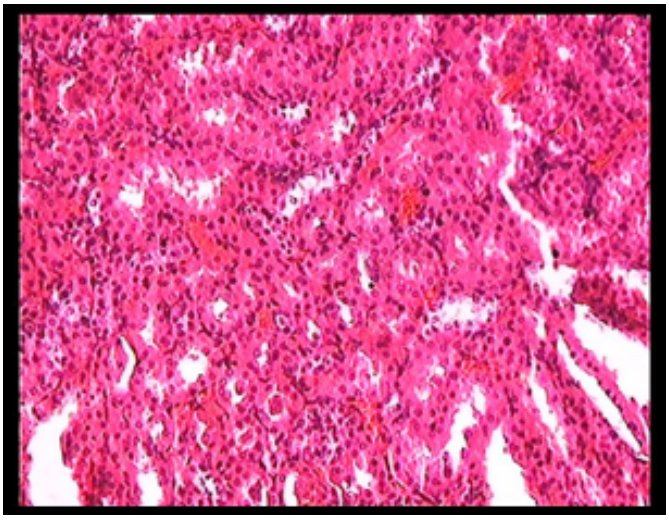


Fig. 3: Photomicrograph of kidney tissues showing coagulative necrosis of KTE cells of many tubules, deposition of debris in the center of the tubules and interstitial haemorrhages. (60 DPT, Group II Treated rats, H&E X100).

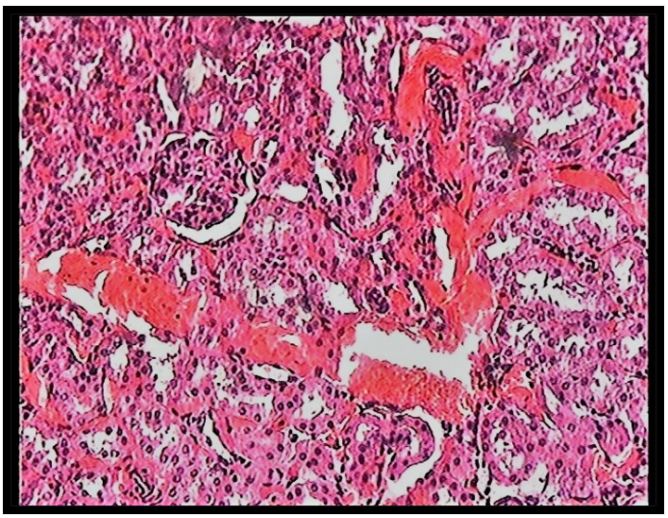


Fig. 4: Photomicrograph of kidney showing congestion of blood vessels and interstitial haemorrhage. (60 DPT, Group II treated rats, H&E X100).

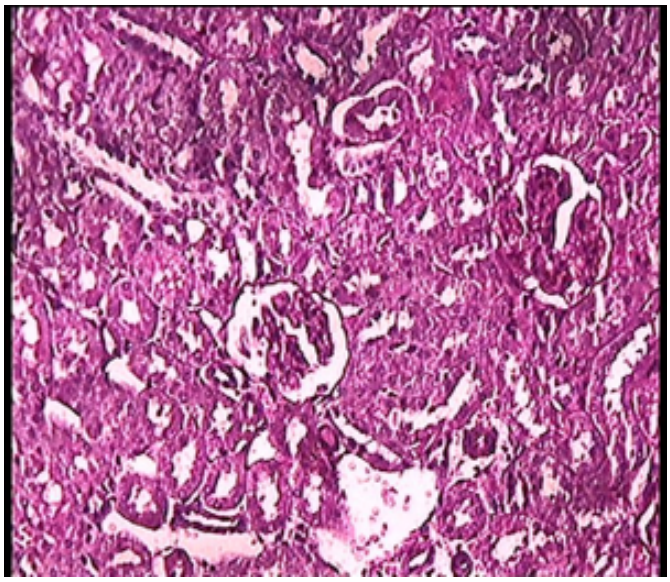


Fig. 5: Photomicrograph of kidney showing "tram- truck" appearance of glomerulus leading to Hyper-lobulated Glomerulus (90 DPT, Group II treated rats, PAS X100).

were also in confirmation with those obtained after oral administration of AgNPs at 50 ppm for 14 days period (Jafarzadeh, 2015). Proliferation of mesangial cells and expansion of mesangial matrix was seen at 60th and 90th day of experiment. Similar findings were reported after AgNPs administration (Sarhan and Hussein, 2014). The reduction in capillary lumen may be a result of injury caused by AgNPs which resulted in swelling and other inflammatory reactions in the endothelial cells of the glomerular capillaries. The increase in mesangial cell number may be a compensatory mechanism of the kidney to maintain its functions. The deformity in the shape of Bowman's capsule may be due to the injury caused by ROS to the epithelial cells of the Bowman's capsule

Immunoperoxidase Reaction

Day 90th kidney tissue samples of treated rats were found to have positive immunoperoxidase reaction which indicated presence of immune complexes in the glomeruli of kidney. The immune complexes were sub-epithelial in nature indicating Type 3 Membrano-Proliferative Glomerulo-Nephritis (Fig. 6). The histopathological lesions found with H&E stained slides were consistent with this finding which showed increase in mesangial cellularity and matrix with infiltrating mononuclear leukocytes to cause

hyper-lobulated tufts. The interstitium, tubules, and vessels showed non-specific changes that correlate with the severity of damage.

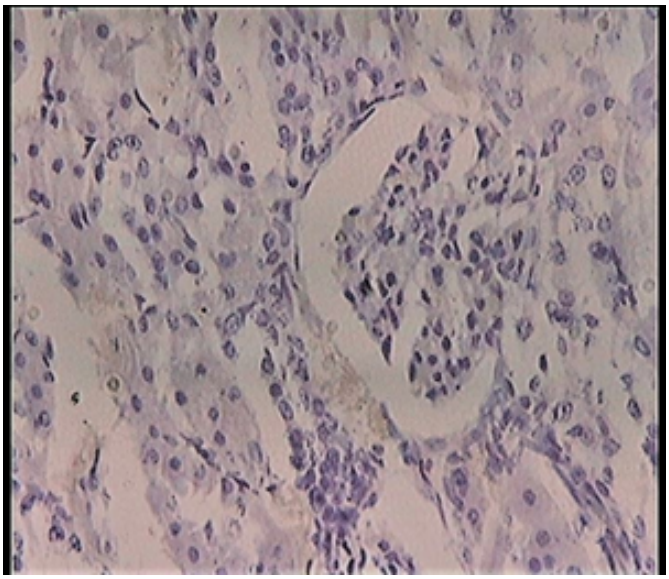


Fig. 6: Photomicrograph of kidney (Immunohistochemistry) showing brown colour immune complex deposition. (90 DPT, Group II treated rats, IHC X100).

Day 90th kidney tissue sections of treated rats showed positive results for the presence of immune complexes in the subepithelial region along with damage to the glomerular basement membrane. This is due to the fact that AgNPs acts as a hapten; however, when these nanoparticles bind with certain body proteins they become antigenic and as a result induce antibody production and thus results in formation of Ag-Ab complexes in body which get deposited in the glomeruli. The immune complex mediated glomerulonephritis have been reported caused by pesticide lindane intake in sheep (Khurana and Chauhan, 2002).

Silver nanoparticles are a common ingredient of food particles, medicines, drug delivery agents, topical ointments or cosmetic and can lead to various toxicities and easily enter through ingestion, inhalation and also through cutaneous route (Zivic *et al.,* 2017) and subsequently due to the small size of these nanoparticles facilitates their translocation from natural barriers is responsible for acute and chronic toxic effects (Jeevanandam *et al*., 2018). According to a survey, AgNPs have been used in 278 different product types, 34 countries and 15 industries, so with this increased incorporation of AgNPs in almost everything ranging from the clothes we wear to the food we eat and the healing ointments and cosmetics and studies have revealed that AgNPs can causes serious adverse effects on the body, particularly the kidneys because kidneys play a very important role in excretion of these nanoparticles from the body.

So, the use of silver nanoparticle should be restricted to very important areas like in biomedical applications so that the exposure of the humans to nanoparticles could be restricted and is within a safety level. Also green synthesized AgNPs should be preferred as compared to chemically synthesized nanoparticles because of their phytoconstituents which have a capping effect and they are shown to have lesser toxicity in kidney tissues as seen by antioxidant activity and cell viability assay (Vasanth and Kurian, 2017). Further different animal models can be used to assess the effect of AgNPs on the body, also varied doses and forms of AgNPs can be used with increased duration of exposure to get a more precise data to conclude the harmful effects of silver nanoparticles in men and animals.

Conclusion

The present study demonstrates that 90-day oral exposure to AgNPs induces renal damage which is evaluated by histopathological analysis. Due to limited sample size and limited time duration and absence of molecular tests, a detailed mechanistic interpretation and broader generalisation of the results cannot be made. Further studies are required in same field.

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