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Evaluation and comparison of the mechanical properties for nano-particles coated mini-implants

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Abstract:
Orthodontic mini-implants provide effective anchorage but remain susceptible to fracture during clinical use. Therefore, it is of interest to evaluate the effect of zinc oxide and silver nanoparticle coatings on mini-implant stability. Hence, thirty-six mini-implants were allocated to uncoated, zinc oxide-coated, and silver-coated groups and tested using artificial bone models. Coated mini-implants demonstrated lower insertion and removal torque than uncoated implants, indicating altered mechanical behavior. Thus, nanoparticle coatings, particularly zinc oxide and silver, may improve mini-implant stability and reduce fracture risk, supporting their potential clinical application.

Keywords: Mini-implants, zinc oxide nanoparticles, silver nanoparticles, insertion torque, removal torque.

Background:
In recent years, there has been a significant revolution in the orthodontic treatment due to the development of technology and materials science. One of these inventions is mini-implants or temporary anchorage devices (TADs), which have become the game changers in orthodontic anchorage. These devices are also beneficial when applied in orthodontic therapy, as they offer greater tooth stability, which is especially helpful in producing effective tooth movement **[1].** Nonetheless, mini-implants have their complications. The loss of a mini-implant is an established fact that may result in increased time and expenses in treatment, and patient discomfort **[2].** The value of the torque applied during the insertion and removal of mini-implants is one of the determinants of the risk of fracturing, and the recent scientific findings suggest that the improvement of the mechanical properties and biocompatibility of materials used in orthodontics is associated with the newly developed nanotechnologies. Zinc oxide and silver nanoparticles have been tested in terms of their antimicrobial and antibacterial properties and the reinforcement of mechanical properties of materials **[3, 4].** Additionally, it has been reported that the application of nanocoatings on mini-implants can decrease the risk of fracture and increase the rate of osseointegration **[5]**. Therefore, it is of interest to compare the effect of zinc oxide and silver nanoparticles coating mini-implants in terms of their insertion and removal torque.

Materials and Methodology:
Sample selection:
The study utilised 36 mini-implants with a diameter of 1.4 mm and a length of 10 mm. This size was chosen based on previous research indicating that mini-implants with diameters of 1.4-1.6 mm and lengths of 8-12 mm are optimal for orthodontic anchorage due to their stability and reduced fracture risk **[6, 7]**.

The samples were divided into three groups:
[1] Group I – Mini-implants without coated surface (n=12)
[2] Group II – Zinc oxide nanoparticles coated mini-implants (n=12)
[3] Group III – Silver nanoparticles coated mini-implants (n=12)

Choosing nanoparticles (NPs):
The antimicrobial properties of nanoparticles underlie the selection of these materials as coating materials. Besides antimicrobial effects, zinc oxide nanoparticles have anti-inflammatory effects, which can be beneficial in treating infections and inflammatory diseases, and therefore, both silver and zinc oxide nanoparticles are useful in a variety of biomedical applications.

Preparation of zinc oxide nanoparticles (ZnONPs):
The precipitation method is the easiest, cheapest and can produce high-quality nanoparticles, so 1 molar of Zinc acetate was dissolved in double-distilled water (200 mL) at 5o C and stirred. 1.5 M of Oxalic acid (H2C2O4·2H2O) dissolved in double-distilled water (200mL) at 5°C was slowly added to the cold solution of Zinc acetate. The solution was stirred at low temperature (2 hours) and the solution slowly changed to a white precipitate. The precipitate was filtered and washed with ethanol and dried at 80 o C in 2 hours to produce Zinc oxalate. The Zinc oxalate was further calcined at 400°C for 2 hours to obtain pure ZnO nanomaterial.

Synthesis of silver nanoparticles (AgNPs):
The use of silver nanoparticles is a popular topic of research due to their distinctive characteristics and possible use in different spheres, such as medicine, electronics, and catalysis. AgNPs can be prepared through a number of different methods, with wet-chemical reduction being one of the most popular **[8, 9].** To prepare silver nanoparticles, two stabilising agents, Sodium Dodecyl Sulphate (SDS) and Sodium Citrate were employed. As a precursor of metal salt and a stabilising agent, respectively, silver nitrate solution (1.0-6.0 mM) and 8% (w/w) SDS were used. Hydrazine hydrate solution with a concentration ranging from 2.0 mM to 12 mM and sodium citrate solution (1.0 mM to 2.0 mM) were used as a reducing agent. Sodium citrate was also used as a stabilising agent at room temperature. When sodium citrate was added as a stabilising agent, the colourless, clear

solution changed to a typical pale yellow and pale red. The presence of colour indicated the formation of silver nanoparticles. Centrifugation was used to purify the silver nanoparticles. The silver colloids were washed at least thrice with deionised water under a stream of nitrogen to remove excess silver ions. A dried powder of the nano-sized silver was obtained by freeze-drying.

Coating methods:
To enhance the surface properties of mini-implants by applying thin films of silver and zinc oxide nanoparticles, different coating techniques have been used. The techniques employed include thermal vacuum evaporation **[10, 11]**, high-vacuum magnetron sputtering **[12],** salinisation **[13],** and electroplating **[14]** and dip-coating in the current study, mini-implants were coated with silver and zinc oxide nanoparticles via an ion beam sputtering machine. This technique was selected since it is capable of making a very pure thin film with a high deposition rate but with minimum damage to the substrate **[15]**. The ion-beam sputtering unit was conducted in a vacuum at a sputtering rate of 1450 L/min and rotational speed of 31500 rpm with a base pressure of 8x10-8T. Localised heaters were used to heat the substrate to 600^{o}C.

Surface morphology:
To determine the surface features of coated and uncoated mini-implants, scanning electron micrographs (SEM) of the surfaces of the specimens. SEM images of the coated mini-implants revealed the even distribution of AgNPs and ZnONPs on mini-implants. On the other hand, the uncoated mini- implants had evident metal striations with a general profile **(Figure 1)**. Moreover, SEM was used to cross-sectionally analyze the coated mini-implants to determine the thickness of the nanoparticle coating. The coating of silver nanoparticles was 106 nm and that of zinc oxide was 87 nm **(Figure 2).**

Study design:
To determine the mechanical properties of mini-implants coated with nanoparticles and uncoated, an *in vitro* experimental study was performed. Polyfoam models have been used in many orthopaedic, dental implant, and mini-implant studies since they are a representation of the density of human bone **[16].** In this research, a model of the synthetic bone, which was closely similar to the density and structure of the human mandible, was applied in the setup to allow standardised and replicative testing. Mechanical testing using synthetic bones has been reported to provide mechanical results similar to those of human cadaver bone and, thus, would be a suitable substitute to *in vivo* testing **[17].** Bredbenner and Haug (2000) **[18]** tested mechanical properties of various bone-substitute materials with orthopaedic implants and human cadaveric bone. They found that the values of insertion torque and pull-out strength calculated with the help of artificial specimens did not differ significantly with those of human cadaveric bone found in their research.

Insertion torque and removal torque in synthetic bone:
The insertion and removal torque value of the mini-implants in synthetic bone was measured using a torque-measuring screwdriver, TOHNICHI MFG CO LTD. The screwdriver is accurate within a range of ±3 per cent and constant readings of torque, which justifies the accuracy observed **[19, 20].** In this experiment, the definition of insertion torque was the moments measured when screwing the mini-implants into the synthetic bone and removal torque was the moments measured when unscrewing the implants out of the synthetic bone. These measurements were in Newton-centimetres (Ncm).

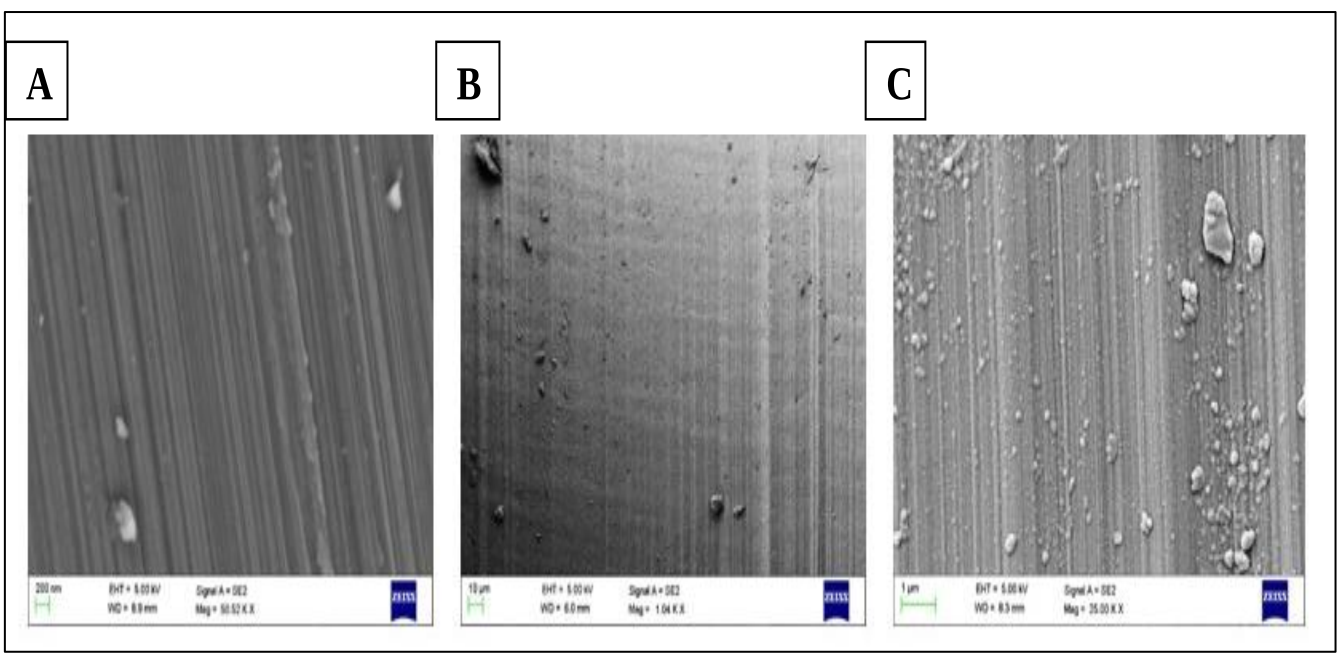

Figure 1: SEM Image of Uncoated (A), ZnONPs-coated (B) and AgNPs-coated (C) mini-implants

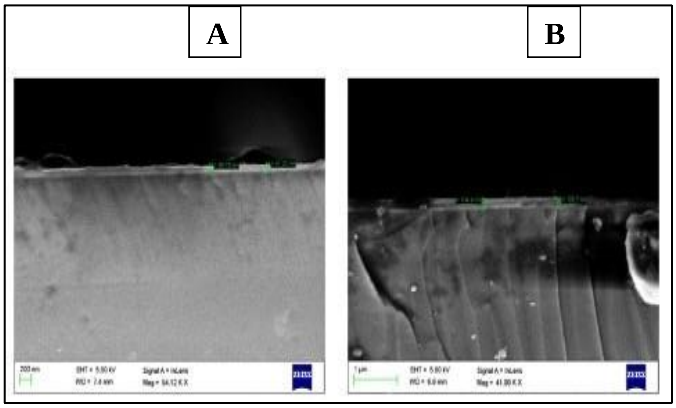

Figure 2: Cross-sectional analysis of SEM indicative of the thickness of ZnONPs (A) and AgNPs (B)

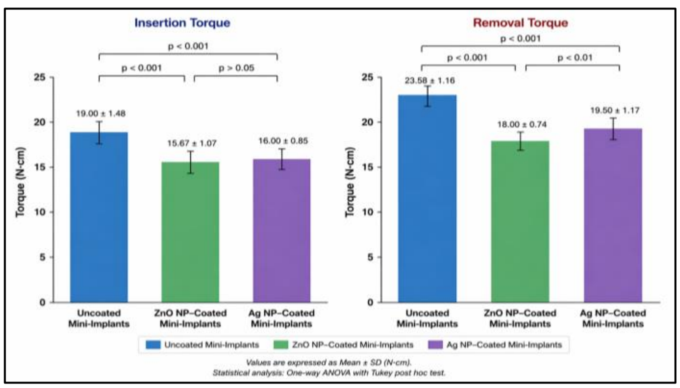

Figure 3: Intergroup comparison of Insertion and Removal Torque

Results:

Paired t-tests were used to compare insertion and removal torque within groups, while independent t-tests were used to compare between groups. All three groups exhibited a significant increase in torque values from insertion to removal ($p < 0.001$), indicating that implants become more stable over time. The uncoated mini-implants showed the highest mean insertion torque (19.00 ± 1.48 Ncm) and removal torque (23.58 ± 1.16 Ncm). The ZnO NP–coated group demonstrated the lowest values (15.67 ± 1.07 Ncm for insertion; 18.00 ± 0.74 Ncm for removal), while the Ag NP–coated group showed intermediate values (16.00 ± 0.85 Ncm for insertion; 19.50 ± 1.17 Ncm for removal) **(Table 1).** Uncoated mini-implants showed significantly higher insertion and removal torque values compared to both coated groups ($p < 0.001$). The mean difference in insertion torque was 3.33 Ncm between uncoated and ZnO NP–coated groups, and 3.00 Ncm between uncoated and Ag NP–coated groups. For removal torque, the mean differences were 5.58 Ncm (uncoated vs ZnO NP) and 4.08 Ncm (uncoated vs Ag NP), respectively. When ZnO NP–coated and Ag NP–coated mini-implants were compared, there was no statistically significant difference in insertion torque values (mean difference = 0.33 Ncm; $p > 0.05$). However, a statistically significant difference was observed in removal torque values between these two groups, with the Ag NP–coated group showing higher values by 1.50 Ncm ($p < 0.01$) **(Table 2; Figure 3).**

Table 1: Intragroup comparison of insertion and removal torque

Group	Insertion Torque (Mean ± SD)	Removal Torque (Mean ± SD)	Intragroup p-value (Insertion vs Removal)
Uncoated Mini-Implants	19.00 ± 1.48	23.58 ± 1.16	<0.001**
ZnO NP–Coated Mini-Implants	15.67 ± 1.07	18.00 ± 0.74	<0.001**
Ag NP–Coated Mini-Implants	16.00 ± 0.85	19.50 ± 1.17	<0.001**

Table 2: Intergroup comparison of insertion and removal torque

Torque	Groups	Mean difference	p-value
Insertion	Uncoated vs ZnO NP	3.33	<0.001**
	Uncoated vs Ag NP	3.00	<0.001**
	ZnO NP vs Ag NP	0.33	>0.05
Removal	Uncoated vs ZnO NP	5.58	<0.001**
	Uncoated vs Ag NP	4.08	<0.001**
	ZnO NP vs Ag NP	1.50	<0.01

Discussion:

Mini-implants have gained popularity in orthodontic therapy due to their ability to provide a good anchorage. The application of mini-implants however is subject to various factors such as primary stability, good osseointegration, and mechanical properties. The effect of silver and zinc oxide nanoparticles in coating the mini-implants on the mechanical properties has been evaluated in the current work. Based on the current data, we have found that the insertion and removal torque values of the coated mini-implants were much lower as compared to the uncoated mini- implants. This study finding is in agreement with other studies that have reported low insertion torque values of coated mini-implants **[21-23].** The observed reductions in the insertion torque in this study can be explained by higher surface roughness and wettability of the coated mini-implants. Silver and zinc oxide nanoparticles coating could also have played a role in lowering the values of insertion torque by reducing friction between the mini-implant and the bone **[24].** We also found that there was a much lower level of loosening (measured in loss of removal torque) with our coated mini-implants compared to our uncoated mini-implants. These findings can be easily compared to previous research that indicated that the removal torque of the coated mini-implants is less than the control **[21, 22 and 25].** The silver and zinc oxide nanoparticle coating might also have adversely impacted the removal torque values by increasing bone formation and decreasing inflammation in the region of the mini-implant. In the comparative analysis, it was found that the present results were lower than those of Suzuki *et al.* (2011), Baldi *et al.* and Sreenivasagan *et al.* that reported lower values of the insertion torque of the coated mini-implants compared to the uncoated mini-implants **[26–28].** Although these are good outcomes, there are a number of weaknesses that are apparent when employing this method. To begin with, the current research was done in a laboratory, which might not be a clinical practice. Secondly, the paper evaluates the effect of silver and zinc oxide nanoparticle coating on the mechanical properties of mini-implants only. More studies should be conducted to evaluate the pros and cons of coated mini-implants in clinical practice; to identify the influence of other coating or surface treatments on the mechanical properties of mini-implants to improve mechanical properties and biocompatibility; and to examine the effects of coated mini-implants on treatment outcomes and patient sensation.

Conclusion:

We show that mini-implants can have their mechanical properties improved by coating them with silver and zinc oxide nanoparticles to reduce insertion and removal torque. According to these results, coated mini-implants can decrease the failure rates and enhance their efficacy in orthodontic treatment. In the present research, it was discovered that the force used in mini-implant therapy does not harm the bone and soft tissue as much as it was thought to be. This can mean that the patients are more relaxed and less likely to develop complications.

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