Use of Antimicrobial Silver Coatings on Fixed Orthodontic Appliances, Including Archwires, Brackets, and Microimplants: A Systematic Review

Magdalena Sycińska-Dziarnowska, Liliana Szyszka-Sommerfeld, Magdalena Ziąbka, Gianrico Spagnuolo, Krzysztof Woźniak

Orthodontic treatments, while essential for achieving optimal oral health, present challenges in infection control due to the propensity for bacterial adhesion and biofilm formation on orthodontic appliances. Silver-coated orthodontic materials have emerged as a promising solution, leveraging the potent antimicrobial properties of silver nanoparticles (AgNPs). Antibacterial coatings are used in orthodontics to prevent the formation of bacterial biofilms. This systematic review evaluated the literature on antimicrobial silver coatings on fixed orthodontic appliances, including archwires, brackets, and microimplants.

Two evaluators, working independently, rigorously conducted a comprehensive search of various databases, including PubMed, PubMed Central, Embase, Scopus, and Web of Science. This systematic review comprehensively examined in vitro studies investigating the antimicrobial efficacy of silver-coated orthodontic archwires, brackets, and microimplants.

The review registered in PROSPERO CRD42024509189 synthesized findings from 18 diverse studies, revealing consistent and significant reductions in bacterial adhesion, biofilm formation, and colony counts with the incorporation of AgNPs. Key studies demonstrated the effectiveness of silver-coated archwires and brackets against common oral bacteria, such as Streptococcus mutans and Staphylococcus aureus. Microimplants coated with AgNPs also exhibited notable antimicrobial activity against a range of microorganisms.

The systematic review revealed potential mechanisms underlying these antimicrobial effects, highlighted implications for infection prevention in orthodontic practice, and suggested future research avenues. Despite some study heterogeneity and limitations, the collective evidence supports the potential of silver-coated orthodontic materials in mitigating bacterial complications, emphasizing their relevance in advancing infection control measures in orthodontics.

Keywords: Orthodontics • Silver • Anti-Infective Agents • Dentistry

Full-text PDF: https://www.medscimonit.com/abstract/index/idArt/944255

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Indexed in: [Current Contents/Clinical Medicine] [SCI Expanded] [ISI Alerting System] [ISI Journals Master List] [Index Medicus/MEDLINE] [EMBASE/Excerpta Medica] [Chemical Abstracts/CAS]
Introduction

Orthodontic treatments are integral to achieving optimal oral health and aesthetic outcomes for individuals with malocclusion. Fixed orthodontic appliances are devices used by orthodontists to straighten and align teeth, correct bite problems, and improve overall dental aesthetics. Unlike removable appliances like aligners, fixed appliances are bonded to the teeth and cannot be easily removed by the patient. They consist of various components, including archwires, brackets, and microimplants, each playing a crucial role in the orthodontic treatment process. Archwires are thin, flexible wires inserted into the brackets attached to the teeth. They exert continuous pressure on the teeth, guiding them into the desired position over time. Archwires come in different materials, including stainless steel, nickel-titanium (NiTi), and beta-titanium alloys. Brackets are small attachments made of metal or ceramic that are bonded to the surface of each tooth. They serve as anchors for the archwire and help transmit forces from the wire to the teeth. Microimplants, also known as temporary anchorage devices (TADs), are small screws or mini-implants that are temporarily placed into the bone to provide additional anchorage during orthodontic treatment. These components are carefully selected and customized by orthodontists based on individual patient needs, treatment goals, and biomechanical principles. However, the use of orthodontic appliances, composed of archwires, brackets, and microimplants, presents a notable challenge in infection control due to the environment conducive to bacterial adhesion and biofilm formation [1]. Biofilm formation with increased levels of bacterial colonization on fixed orthodontic appliances poses significant risks to oral health, including dental caries, gingival inflammation, white spot lesions, and periodontal disease [2]. Plaque index values during orthodontic treatment were reportedly significantly higher than in the control group [3].

In response to this concern, the exploration of innovative solutions has accelerated, and a promising avenue involves integrating antimicrobial agents into orthodontic materials [4]. Among these agents, silver has gained recognition for its robust antimicrobial properties. In dentistry, acrylic resins used for removable dentures in prosthetics, composite resins in dental restorative treatment, root canal sterilization, composite materials used in orthodontic treatment, membranes used for guided tissue regeneration in periodontology, and titanium coatings applied in dental implant treatment can all contain silver nanoparticles [5,6]. The findings outlined in the study conducted by Sodagar et al showed that composite discs infused with 5% and 10% concentrations of silver/hydroxyapatite nanoparticles exhibit the formation of bacterial growth inhibition zones, demonstrating notable antibacterial efficacy against biofilms [7]. Silver, known for its potent antimicrobial properties, has been extensively studied as a coating material for orthodontic appliances [8-11]. This systematic review meticulously examined the existing literature on antimicrobial innovations in orthodontics, specifically focusing on coatings containing silver applied to archwires, brackets, and microimplants [12-14]. By synthesizing findings from a diverse array of studies, this review seeks to provide a comprehensive understanding of the efficacy of silver-based coatings in preventing microbial adhesion, colonization, and biofilm formation on orthodontic appliances.

Despite the potential benefits of silver-based coatings, a critical evaluation of the existing literature reveals gaps in understanding the extent to which these coatings effectively mitigate bacterial adhesion and biofilm formation on various orthodontic surfaces. While individual studies have demonstrated promising results, a systematic review is necessary to consolidate and analyze these findings comprehensively. The present review seeks to fill this gap by critically examining the methodologies, outcomes, and limitations of diverse studies, thereby providing a synthesized perspective on the antimicrobial efficacy of silver-coated orthodontic materials. The exploration of this topic is particularly timely given the increasing emphasis on infection control in dentistry and the continuous evolution of orthodontic materials and technologies.

With the overarching goal of advancing infection control measures in orthodontic practice, this systematic review posed the following research question: What is the current evidence regarding the antimicrobial efficacy of coatings containing silver on orthodontic archwires, brackets, and microimplants in preventing microbial colonization, adhesion, and biofilm formation? Therefore, this systematic review evaluated the literature on antimicrobial silver coatings on fixed orthodontic appliances, including archwires, brackets, and microimplants.

Material and Methods

To enhance transparency and adherence to systematic review guidelines, the study protocol was registered in PROSPERO CRD42024509189. The inclusion process and subsequent screening are visually represented through the creation of a PRISMA diagram (Figure 1), divided into identification, screening, and inclusion subsections, allowing for a clear representation of the entire search strategy [15].

Search Strategy

Two independent evaluators systematically conducted a thorough search in the databases PubMed, PubMed Central, Embase, Scopus, and Web of Science. The search query, initially prepared for PubMed: (“orthodontic***”) AND (“silver nanoparticle***” or “nano silver”) AND (“wire***” OR “archwire***” OR...
Identification of studies via databases and registers

Records identified from:
- Databases (n=5)
  - PubMed
  - 420 PubMed Central
  - Embase
  - Scopus
  - Web of Science
- Registers (n=702)
  - 56 PubMed
  - 420 PubMed Central
  - 62 Embase
  - 78 Scopus
  - 86 Web of Science

Records removed before screening:
- Duplicate records removed (n=193)

Records screened (n=509)

Reports assessed for eligibility (n=40)

Reports not retrieved (n=0)

Reports sought for retrieval (n=40)

Records excluded (n=469)

Studies included in the review (n=18)

PubMed: 56

(“orthodontic*”) AND (“silver nanoparticle*” or “nano silver”) AND (“wire*” OR “archwire*” OR “braces” OR “bracket*” OR “minimplant*” OR “microimplant*” OR “screw*” OR “surface” OR “appliance*”)

PMC: 420

(“orthodontic”) AND (“silver nanoparticle” or “nano silver”) AND (“wire” OR “archwire” OR “braces” OR “bracket” OR “minimplant” OR “microimplant” OR “screw” OR “surface” OR “appliance”)

Embase: 62

(“orthodontic*” OR “orthodontic”/exp) AND (“silver nanoparticle*” OR “nano silver” OR “nano silver”/exp) AND (“wire*” OR “archwire*” OR “braces” OR “bracket*” OR “minimplant*” OR “microimplant*” OR “screw*” OR “surface” OR “appliance*”)

Scopus: 78

TITLE-ABS-KEY (( “orthodontic*” ) AND ( “silver nanoparticle*” OR “nano silver” ) AND ( “wire*” OR “archwire*” OR “braces” OR “bracket*” OR “minimplant*” OR “microimplant*” OR “screw*” OR “surface” OR “appliance*” ))

Web of Science: 86

[All Fields] (“orthodontic*”) AND (“silver nanoparticle*” or “nano silver”) AND (“wire*” OR “archwire*” OR “braces” OR “bracket*” OR “minimplant*” OR “microimplant*” OR “screw*” OR “surface” OR “appliance*”)
“braces” OR “bracket”* OR “minimplant”* OR “microimplant”* OR “screw”* OR “surface” OR “appliance”), was subsequently adapted for application to other databases, as illustrated in **Figure 2**. After completing a comprehensive search, all duplicate records were removed.

The present systematic review was structured according to the PICO framework [16] and focused on populations and interventions. Population: In vitro studies that investigate the incorporation of silver nanoparticles or layer enriched silver obtained by various methods into metal orthodontic devices, such as archwires, orthodontic brackets, and microimplants, to assess their potential antimicrobial capabilities. Intervention: Incorporation of silver particles onto the surface of metal orthodontic devices. The review compared these silver-coated devices against metal surfaces of orthodontic devices lacking silver agents, with the outcome of interest being the evaluation of antimicrobial activity. The research question being addressed was whether incorporating silver particles onto metal orthodontic devices enhances their antimicrobial activity in vitro studies.

The literature search was completed on February 15, 2024, with no limitations placed on publication dates to ensure a comprehensive review of relevant articles. The review process was conducted in an unbiased manner to maintain objectivity.

**Eligibility Criteria**

We included in vitro studies that specifically evaluated the antimicrobial activity of silver nanoparticles when applied to the surface of metal orthodontic devices. We excluded literature reviews, systematic reviews, case reports, animal studies, and studies focused on the incorporation of silver nanoparticles into orthodontic bonding systems.

**Data Extraction**

After eliminating duplicate publications, the first author (M.S.-D.) thoroughly examined the titles and abstracts of the remaining studies. Subsequently, the second author (L.S.-S.) also assessed all studies to identify potentially eligible ones. The full texts of the selected papers were carefully reviewed, and decisions regarding their inclusion or exclusion were made based on predetermined criteria. Any uncertainties or ambiguities that arose during this process were resolved through discussions between these 2 authors and the third author (K.W.). These allowed for a collaborative approach to addressing any disagreements or uncertainties, ensuring a comprehensive and reliable review process. To facilitate the comparative analysis of the chosen studies, a spreadsheet was generated in accordance with the Cochrane Collaboration guidelines. Cohen’s Kappa statistic was used to assess the level of agreement between authors.

**Quality Assessment**

In this review, the quality assessment of included studies was conducted using the Newcastle-Ottawa Scale (NOS) [17]. The NOS scoring system assigns higher scores to studies demonstrating better methodological quality. The scale considers 3 domains: selection of study groups, comparability of groups, and assessment of outcomes or exposure. Each domain comprises criteria that are meticulously evaluated to calculate the overall quality score for each study. The assessment process was carried out independently by 2 reviewers (M.S.-D. and L.S.-S.), who engaged in discussions and consultations with a third author (K.W.) to resolve any uncertainties or disagreements. To quantify the level of agreement among the authors, the Cohen’s Kappa coefficient was calculated. This rigorous evaluation using NOS allowed for an objective assessment of the included studies’ methodological rigor and their contribution to the collective body of evidence.

**Statistical Analysis**

Cohen’s Kappa coefficient was calculated using the R software package to assess the concordance between authors.

**Results**

**Search Strategy and Study Selection**

The search strategy yielded a total of 702 potential articles, with contributions from various databases: 56 from PubMed, 420 from PubMed Central, 62 from Embase, 78 from Scopus, and 86 from Web of Science. After eliminating 193 duplicate records, the remaining articles underwent thorough analysis. Next, 469 papers were excluded as they did not meet the predefined inclusion criteria. Of the initial pool of 40 articles, 22 were excluded due to lack of relevance to the topic of the study. The final qualitative synthesis comprised 18 papers.

**Systematic Review Process**

The systematic review process was visually represented in the PRISMA Flow Diagram (**Figure 1**), offering a detailed depiction of each stage, including the initial search, screening, and selection. This diagram, following the PRISMA guidelines, provides transparency and clarity in outlining the systematic review’s progression. The agreement between the 2 reviewers demonstrated robust consistency, with a high Cohen’s Kappa coefficient of 0.97. The high level of agreement enhances the reliability and credibility of the systematic review’s findings.
Table 1. Summary of studies investigating antimicrobial coatings on orthodontic wires, brackets and microimplants: Materials and methods.

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Material</th>
<th>Antimicrobial method</th>
<th>Coating composition AgNPs size, %</th>
<th>Coating technique</th>
<th>Bacteria/ fungi tested</th>
<th>Surface characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anand, 2023 [33]</td>
<td>SS wires</td>
<td>inhibition zone</td>
<td>AgNPs Size: 20-60 nm</td>
<td>Electrochemical deposition</td>
<td>E.coli, P. aeruginosa, Enterobacter, S. albus</td>
<td>TEM, DLS, XDR</td>
</tr>
<tr>
<td>Bącela, 2022 [19]</td>
<td>SS orthodontic wires coated with a thin TiO₂: Ag film and control group</td>
<td>CFU, biofilm formation</td>
<td>TiO₂: Ag</td>
<td>Sol-gel dip-coating</td>
<td>S. mutans</td>
<td></td>
</tr>
<tr>
<td>Espinosa-Cristóbal, 2018 [10]</td>
<td>NiTi, CuNiTi, and SS and SS brackets</td>
<td>MIC, PCR</td>
<td>AgNPs Size: 8.1 nm and 20.1 nm</td>
<td>Chemical reduction process</td>
<td>S. mutans</td>
<td>AFM, SEM</td>
</tr>
<tr>
<td>Farheen, 2022 [27]</td>
<td>NiTi orthodontic wires</td>
<td>CFU, biofilm formation</td>
<td>AgNPs Size: 30-80 nm</td>
<td>The synthesis of AgNPs using Hibiscus rosa-sinensis flower extract involves a bio-reduction process</td>
<td>E. coli, L. monocytogenes, S. mutans</td>
<td>TEM, DLS, zeta potential, FTIR, and UV-Vis</td>
</tr>
<tr>
<td>Gil, 2020 [21]</td>
<td>NiTi orthodontic wires</td>
<td>CFU</td>
<td>AgNPs Size: 40 nm</td>
<td>Electrodeposition</td>
<td>L. salivarius, S. sanguinis</td>
<td>Mechanical test, Niion release test</td>
</tr>
<tr>
<td>Gonçalves, 2020 [20]</td>
<td>SS orthodontic wires of 2 brands and control group</td>
<td>CFU, biofilm formation</td>
<td>AgNPs Size: &gt;20 nm</td>
<td>Hydrothermal synthesis AgNO₃ solution used as silver precursors</td>
<td>S. aureus, S. mutans</td>
<td>DSC, SEM, XRD</td>
</tr>
<tr>
<td>Lee, 2020 [28]</td>
<td>SS samples</td>
<td>Colonies counts</td>
<td>AgNPs Size: not mentioned</td>
<td>Layer-by-layer deposition matrices on SS with reduction of Ag+ to form AgNPs</td>
<td>E.coli, S. mutans</td>
<td>SEM, XPS</td>
</tr>
<tr>
<td>Mhaske, 2015 [12]</td>
<td>NiTi and SS archwires</td>
<td>CFU, bacterial adherence test</td>
<td>Pure silver 99.9%</td>
<td>Thermal vacuum evaporation</td>
<td>L. acidophilus</td>
<td></td>
</tr>
<tr>
<td>Nafarrate-Valdez, 2022 [18]</td>
<td>Orthodontic wires: SS, CuNiTi, NiTi and control</td>
<td>MIC and bacterial adherence test</td>
<td>AgNPs Size: 30 nm</td>
<td>Chemical reduction</td>
<td>S. mutans</td>
<td>AFM, DLS, SEM, TEM</td>
</tr>
</tbody>
</table>
Table 1 continued. Summary of studies investigating antimicrobial coatings on orthodontic wires, brackets and microimplants: Materials and methods.

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Material</th>
<th>Antimicrobial method</th>
<th>Coating composition AgNPs size, %</th>
<th>Coating technique</th>
<th>Bacteria/ fungi tested</th>
<th>Surface characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ameli, 2022 [23]</td>
<td>20 stainless steel brackets, 4 groups 5 brackets per group, coated with copper oxide nanoparticles (CuO-NPs), titanium dioxide nanoparticles (TiO(_2)-NPs), and hydroxyapatite silver nanoparticles (HA-AgNPs)</td>
<td>Colony counts</td>
<td>AgNPs Size: &lt;100 nm</td>
<td>Dip coating</td>
<td>S. mutans</td>
<td>AFM, SEM</td>
</tr>
<tr>
<td>Ghasemi, 2017 [22]</td>
<td>55 stainless steel brackets 5 groups of 11 brackets each: silver-coated and titanium-coated and control group</td>
<td>Colony counts</td>
<td>AgNPs Size: 60 nm and 100 nm</td>
<td>Physical vapor deposition</td>
<td>S. mutans</td>
<td>AFM, SEM, friction test</td>
</tr>
<tr>
<td>Jasso-Ruiz, 2019 [11]</td>
<td>Brackets (metallic and esthetic) 50 brackets: 5 groups; 10 group each with control group</td>
<td>Agar disk diffusion test – inhibition zones</td>
<td>AgNPs Size: &lt;5 nm</td>
<td>In situ chemical reduction</td>
<td>E. coli, S. aureus</td>
<td>SEM, TEM</td>
</tr>
<tr>
<td>Jasso-Ruiz, 2020 [24]</td>
<td>300 commercial orthodontic brackets were used (30 per group) and classified into 10 groups of brackets (5 groups with silver nanoparticles and 5 control groups)</td>
<td>Level of bacterial colonization radioactive marker was used to codify the bacteria and measure the radiation</td>
<td>AgNPs Size: not mentioned</td>
<td>In situ chemical reduction</td>
<td>S. mutans, S. sobrinus</td>
<td>SEM</td>
</tr>
<tr>
<td>Ryu, 2012 [25]</td>
<td>SS samples discs coated with 100 wt% Ag with Ag–1 wt% Pt, and Ag–3 wt% Pt, Discs coated with Ag–7 wt% Pt</td>
<td>CFU, biofilm formation</td>
<td>Ag, Ag-Pt coatings Thickness: from 1.03 to 2.34 (\mu)m</td>
<td>Physical vapor deposition</td>
<td>A. actinomyces-tecomcomits, S. mutans</td>
<td>SEM EDS, Vickers hardness, Potentiodynamic polarization, ICP-AES</td>
</tr>
</tbody>
</table>
Table 1 continued. Summary of studies investigating antimicrobial coatings on orthodontic wires, brackets and microimplants: Materials and methods.

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Material</th>
<th>Antimicrobial method</th>
<th>Coating composition</th>
<th>Coating technique</th>
<th>Bacteria/fungi tested</th>
<th>Surface characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zeidan, 2022 [13]</td>
<td>48 stainless steel brackets, 4 groups each 12 brackets: Ag nanoparticles coated group, ZnO nanoparticles coated group and Ag/ZnO nanoparticles coated group, control group</td>
<td>CFU</td>
<td>AgNPs Size: &lt;40 nm</td>
<td>Physical vapor deposition</td>
<td>L. acidophilus, S. mutans</td>
<td>AFM, XRD</td>
</tr>
</tbody>
</table>

Microimplants

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Material</th>
<th>Antimicrobial method</th>
<th>Coating composition</th>
<th>Coating technique</th>
<th>Bacteria/fungi tested</th>
<th>Surface characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fathy Abo-Elmahasen, 2023 [26]</td>
<td>Orthodontic mini-screws, 2 groups Ag/HA NPs and ZnO NPs no control group</td>
<td>Agar disk diffusion test – inhibition zones</td>
<td>Ag/HA NPs Size: 40-70 nm</td>
<td>Electrochemical deposition</td>
<td>E. aeruginosa, E.coli, E. faecalis, S. aureus, S. mutans, C. albicans</td>
<td>SEM, EDS, XRD, scratching test</td>
</tr>
<tr>
<td>Subramanian, 2022 [9]</td>
<td>Mini-implant (Ti-6Al-4V) AgNPs with biopolymer (Ti-BP-AgNP) and group with SeNP (Ti-BPSeNP) and control group</td>
<td>Agar disk diffusion test - inhibition zones</td>
<td>AgNPs with biopolymer (Ti-BP-AgNP) Size: 50-80 nm</td>
<td>dip-coating technique</td>
<td>Lactobacillus, S. aureus, S. mutans</td>
<td>SEM, XRD</td>
</tr>
<tr>
<td>Venugopal, 2017 [14]</td>
<td>microimplants (Ti6Al4V) AgNPs 2 groups: AgNPs (Ti-AgNPs) and AgNPs-coated biopolymer (Ti-BP-AgNPs) and control group</td>
<td>Agar disk diffusion test – inhibition zones</td>
<td>AgNPs Size: 10-30 nm</td>
<td>The process involved 3 stages: preparation of the hydroxyapatite/chitosan biopolymer, biopolymer layer formation over the Ti6Al4V microimplant surface; and deposition of the AgNPs on the titanium-biopolymer coating by photoreduction of Ag ions</td>
<td>A. actinomycetemcomitans, S. mutans, S. sanguinis</td>
<td>SEM, XPS</td>
</tr>
</tbody>
</table>

Key findings

The materials demonstrated effectiveness against all 3 bacteria cultures tested. The incorporation of silver nanoparticles reduced the presence of bacteria by more than 90%. This antibacterial effect was achieved without any change in colorimetric and mechanical properties, nor did it affect the levels of nickel release from NiTi wires.

Both size of AgNPs demonstrated the capacity to impede the adhesion and growth of S. mutans on the surfaces of orthodontic brackets and orthodontic wires. However, the smaller AgNPs had more notable impact.

The coated brackets exhibited a significant decrease in bacterial colony counts (P<0.05) compared to control groups. Coating did not affect physio-chemical properties of wires, and wires demonstrated efficiency in preventing bacterial adhesion and inhibiting the formation of biofilm by S. aureus and S. mutans.

The antibacterial effect observed during in vitro evaluation of brackets coated with AgNPs against S. mutans, L. acidophilus, S. aureus, and E. coli was high. When compared to the control brackets, those with the AgNPs displayed a significant inhibitory effect on microbial growth.

Reduced bacterial adhesion for both types of microorganisms was observed in all groups with AgNPs compared to control groups.

The bacterial growth on the specimens coated with silver was significantly decreased, with an approximate reduction of 60%.

In comparison to the uncoated bracket, all types of coatings displayed greater antibacterial effect against L. monocytogenes, demonstrating significant antimicrobial and anti-biofilm activities.

Table 2. Studies Investigating antimicrobial coatings on orthodontic wires, brackets and microimplants: Key findings.

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Key findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anand, 2023 [33]</td>
<td>The bacterial cell membrane was disrupted by silver ions, as confirmed by TEM examination</td>
</tr>
<tr>
<td>Baçela, 2022 [19]</td>
<td>After 4 h, the TiO₂: Ag coated surface exhibited a significant reduction in S. mutans bacterial adhesion to the wire, achieving a 74% decrease, statistically significant at a p-value less than 0.05. The utilization of stainless-steel wires with a TiO₂: Ag coating provides not only suitable antimicrobial activity but also demonstrates resistance to biofilm formation</td>
</tr>
<tr>
<td>Espinosa-Cristóbal, 2018 [10]</td>
<td>The antimicrobial inhibition effects against S. mutans were superior in smaller AgNPs samples compared to larger AgNPs demonstrating significant differences between 2 groups (P&lt;0.05). Both size of AgNPs demonstrated the capacity to impede the adhesion and growth of S. mutans on the surfaces of orthodontic brackets and orthodontic wires. However, the smaller AgNPs had more notable impact</td>
</tr>
<tr>
<td>Farheen, 2022 [27]</td>
<td>The AgNPs exhibited notable inhibitory and anti-biofilm effects against S. mutans, E. coli and L. monocytogenes, demonstrating significant antimicrobial and anti-biofilm activities</td>
</tr>
<tr>
<td>Gil, 2020 [21]</td>
<td>The incorporation of silver nanoparticles reduced the presence of bacteria by more than 90%. This antimicrobial effect was achieved without any change in colorimetric and mechanical properties, nor did it affect the levels of nickel release from NiTi wires</td>
</tr>
<tr>
<td>Goncalves, 2020 [20]</td>
<td>The biofilm formation by S. mutans demonstrated statistical significance (p&lt;0.05) when compared to the control group. Coating did not affect physio-chemical properties of wires, and wires demonstrated efficacy in preventing bacterial adhesion and inhibiting the formation of biofilm by S. aureus and S. mutans</td>
</tr>
<tr>
<td>Lee, 2020 [28]</td>
<td>The materials demonstrated effectiveness against E. coli and S. mutans. The surfaces exhibit antibacterial properties that are capable of combating these common bacteria</td>
</tr>
<tr>
<td>Mhaske, 2015 [12]</td>
<td>When compared to the groups containing uncoated wires, the groups containing surface-modified wires exhibited a statistically significant decrease in the survival rate of L. acidophilus, as expressed by CFU. Uncoated stainless steel (836.60±48.97), silver-modified stainless steel (220.90±30.73), uncoated NiTi (748.90±35.64), and surface-modified NiTi (203.20±41.94) exhibited a statistically significant decrease in bacterial survival rate compared to the control group at 90 days, indicating strong antibacterial efficacy (P&lt;0.001)</td>
</tr>
<tr>
<td>Nafarrate-Valdez, 2022 [18]</td>
<td>AgNPs significantly reduced the adhesion and growth capacity of S. mutans on the surfaces of conventional orthodontic archwires, and demonstrated the anti-adherent and antimicrobial properties associated with the incorporation of AgNPs into these materials</td>
</tr>
<tr>
<td>Ameli, 2022 [23]</td>
<td>The average colony count for the 3 experimental groups showed a significant difference compared to the control group at 90 days, indicating strong antibacterial efficacy (P&lt;0.001)</td>
</tr>
<tr>
<td>Ghasemi, 2017 [22]</td>
<td>The coated brackets exhibited a significant decrease in bacterial colony counts (P&lt;0.05)</td>
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<td>Ryu, 2012 [25]</td>
<td>The bacterial growth on the specimens coated with silver was significantly decreased, with an approximate reduction of 60%</td>
</tr>
<tr>
<td>Zeidan, 2022 [13]</td>
<td>In comparison to the uncoated bracket, all types of coatings displayed greater antibacterial effect (P&lt;0.05)</td>
</tr>
<tr>
<td>Fathy Abo-Elmahasen, 2023 [26]</td>
<td>The antimicrobial activity of the tested microimplants was observed against all the investigated microorganisms (against Gram-positive, Gram-negative and fungal strains)</td>
</tr>
<tr>
<td>Subramanian, 2022 [9]</td>
<td>Ti-BP-AgNPs exhibited antibacterial effects against Lactobacillus and S. aureus bacteria. Regarding S. mutans the zone of inhibition was slightly smaller compared to other bacteria</td>
</tr>
<tr>
<td>Venugopal, 2017 [14]</td>
<td>The Ti-BP-AgNP microimplants showed strong antimicrobial activity with clear zones of inhibition against all 3 bacteria cultures tested</td>
</tr>
</tbody>
</table>

AgNPs – silver nanoparticles; CFU – Colony Forming Unit; TEM – Transmission Electron Microscopy; NiTi – archwires: nickel-titanium.
Antimicrobial Coatings on Orthodontic Wires

Several studies investigated the antimicrobial properties of orthodontic wires coated or modified with AgNPs (Tables 1, Table 2). Nafarrate-Valdez et al found that AgNPs significantly reduced the adhesion and growth capacity of *S. mutans* on conventional orthodontic archwires, demonstrating anti-adherent and antimicrobial properties [18]. The study utilized minimal inhibitory concentrations (MIC) and bacterial adherence testing, revealing a size of 30 nm for the AgNPs synthesized through chemical reduction. Bącela et al reported a significant reduction in *S. mutans* bacterial adhesion to stainless steel wires coated with TiO<sub>2</sub>: Ag, showing both antimicrobial activity and resistance to biofilm formation [19]. Gonçalves et al observed statistically significant reductions in biofilm formation by *S. mutans* and *S. aureus* on coated stainless-steel wires [20]. Gil et al found revealed that the incorporation of silver nanoparticles reduced bacterial presence by over 90% without altering colorimetric and mechanical properties or affecting nickel ions release from NiTi wires [21].

Antimicrobial Coatings on Orthodontic Brackets

Studies on orthodontic brackets revealed promising results (Tables 1, 2). Ghasemi et al reported a significant decrease in bacterial colony counts on coated bracket, with results being statistically significant (P<0.05) [22], while Ameli et al demonstrated strong antibacterial efficacy of brackets coated with hydroxyapatite and silver nanoparticles against *S. mutans* [23]. Jasso-Ruiz observed reduced bacterial adhesion in all groups with AgNPs compared to control groups [24], and also found significant inhibitory effects on microbial growth with AgNPs-coated brackets against *S. aureus* and *E. coli* [11]. Moreover, Zeidan et al reported greater antibacterial effects for all types of coated brackets compared to uncoated ones [13]. Ryu et al found a significant decrease in bacterial growth on silver-coated specimens, achieving an approximate 60% reduction [25].

Antimicrobial Coatings on Orthodontic Microimplants

Research on microimplants showed positive outcomes (Table 2). Subramanian et al reported antibacterial effects of Ti-BP-AgNPs against *Lactobacillus* and *S. aureus*, with a slightly smaller zones of inhibition against *S. mutans* [9], while Fathy Abo-Elmahasen et al [26] observed antimicrobial activity against various microorganisms, including Gram-positive, Gram-negative, and fungal strains, in tested microimplants. Venugopal et al noted strong antimicrobial activity of Ti-BP-AgNPs microimplants against 3 bacterial cultures [14].

Surface Characterization Methods

In the reviewed studies, various surface characterization methods were employed to analyze the coated orthodontic
materials (Table 1). Scanning electron microscopy (SEM) was frequently utilized to examine the surface morphology and structure, providing detailed images at the microscale. Transmission electron microscopy (TEM) allowed for even finer visualization, offering insights into the nanoscale features of the coatings.

Bacterial Strains Tested

Regarding the bacteria tested, different studies assessed the antimicrobial efficacy of silver-coated orthodontic materials against various strains (Table 1). For instance, S. mutans, a common bacterium associated with dental caries, was a recurrent choice for evaluating bacterial adhesion and biofilm formation [10,18-20,23,22,25,27,28]. Other bacteria tested included S. aureus, E. coli, L. monocytogenes, and Lactobacillus, representing a spectrum of Gram-positive and Gram-negative bacteria with different pathogenic characteristics [9,13,20,27,28].

Quality Assessment of Studies

Table 3 succinctly summarizes the outcomes of the quality assessment, demonstrating a high level of agreement among evaluators (Cohen’s Kappa coefficient 0.94). The majority of studies achieved a creditable score of 7/9 on the NOS assessment [17], indicating overall good quality. Despite this positive trend, a noticeable heterogeneity persists across various aspects, encompassing study designs, sample characteristics, and methodologies. The aggregate exploration of silver-containing coatings in orthodontics was shown in the reviewed studies; however, the variety of materials used made meta-analysis impossible.

Summary of Findings

In summary, the incorporation of AgNPs into orthodontic wires, brackets, and microimplants demonstrated significant antimicrobial effects against various bacteria, particularly S. mutans. The coated surfaces exhibited reduced bacterial adhesion, inhibited biofilm formation, and, in some cases, showed statistically significant decreases in bacterial colony counts.

Discussion

This systematic review explored the antimicrobial efficacy of silver-coated orthodontic materials, focusing on archwires, brackets, and microimplants. The principal findings revealed consistent and significant antimicrobial effects across various studies, providing valuable insights into the potential of silver coatings in preventing bacterial adhesion and biofilm formation on orthodontic surfaces.

The studies reviewed consistently demonstrated that the incorporation of AgNPs onto orthodontic wires, brackets, and microimplants led to notable reductions in bacterial adhesion, inhibited biofilm formation, and, in some cases, resulted in statistically significant decreases in bacterial colony counts [13,22,23]. Nafarrate-Valdez et al demonstrated significant reductions in S. mutans adhesion and growth on AgNPs-coated orthodontic archwires [18]. Bącela et al reported a 74% decrease in S. mutans adhesion to stainless steel wires [19]. Moreover, Gonçalves et al found significant reductions in biofilm formation by S. mutans and S. aureus on coated stainless-steel wires [20]. Lee et al used layer-by-layer deposition for SS samples, demonstrating antimicrobial efficacy against S. mutans and E. coli, with surface characterization through SEM and XPS [28]. Furthermore, Farheen et al focused on NiTi orthodontic wires, utilizing CFU and biofilm formation assays against S. mutans, E. coli, and L. monocytogenes [27]. In a subsequent study, similar antimicrobial effectiveness against S. sanguinis and L. salivarius was observed [21]. Mhaske et al investigated NiTi and SS archwires, demonstrating antimicrobial efficacy against L. acidophilus [12]. Finally, Espinosa-Cristóbal et al explored NiTi, CuNiTi, and stainless steel archwires, showing antibacterial properties against tested pathogens [10]. Regarding orthodontic brackets, Ghasemi et al reported a notable decrease in bacterial colony counts on coated brackets [22], while Ameli et al showed strong antibacterial efficacy against S. mutans [23]. Jasso-Ruiz et al demonstrated consistently reduced bacterial adhesion and inhibitory effects on microbial growth with AgNPs-coated brackets against S. aureus and E. coli [11,24]. Furthermore, Zeidan et al supported these findings, reporting greater antibacterial effects for all types of coated brackets compared to uncoated ones. These results collectively highlight the promising antimicrobial effects of AgNPs-coated orthodontic materials.

The antimicrobial effects observed in these studies can be attributed to the well-established properties of silver as a potent antimicrobial agent [29]. Silver nanoparticles have been known to exhibit antimicrobial activity by interfering with bacterial cell membranes, disrupting cellular functions, and causing oxidative stress. The small size of AgNPs allows them to penetrate bacterial cells, leading to structural damage and, ultimately, bacterial death [5].

Smaller particle size is associated with increased toxicity, while increased doses and agglomeration of AgNPs further enhance cytotoxicity. In general, most AgNPs exhibit toxicity to the human body, largely due to their small particle size, which facilitates penetration into human tissues [30,31]. The smaller AgNPs exhibited superior antimicrobial inhibition effects against S. mutans compared to larger AgNPs, indicating significant differences between the 2 groups (P<0.05) [10]. In terms of AgNPs sizes, the included studies presented a range of dimensions. Examples include AgNPs with sizes of 30 nm, 40 nm, 8.1 nm, and 60-100
These variations in particle size highlight the diversity in synthesis methods and coating techniques, emphasizing the importance of understanding how characteristics of different AgNPs influence antimicrobial properties. This systematic review underscores the potential of silver-coated orthodontic materials in enhancing infection control during orthodontic treatments. The findings suggest that such coatings can effectively mitigate bacterial adhesion, inhibit biofilm formation, and reduce bacterial colony counts. These implications are particularly relevant in the context of infection prevention in orthodontic practice, where the risk of bacterial complications is inherent due to the use of orthodontic appliances. S. mutans, a well-known caries-causing organism, was frequently analyzed in the included studies [10,18-20, 23,22,25,27,28].

Future research in this area should explore the long-term effects and durability of silver coatings on orthodontic materials. Additionally, investigations into the potential cytotoxic effects and biocompatibility of these coatings would contribute valuable information for their clinical application. Studies comparing the effectiveness of different coating techniques, silver nanoparticle sizes, and concentrations could provide insights into optimizing antimicrobial properties while minimizing potential adverse effects. While AgNPs have shown promise in orthodontic applications due to their antimicrobial properties, it is essential to consider their potential impact on patients’ health. AgNPs have been reported to exert cytotoxic effects on various cell types in vitro, raising concerns about their biocompatibility and safety for clinical use. Moreover, there is evidence suggesting that AgNPs can accumulate in various tissues and organs, potentially leading to systemic toxicity over prolonged exposure periods [30]. It is important for clinicians to weigh the benefits of using AgNPs-coated orthodontic materials against the potential risks to patients’ health. Close monitoring and periodic assessments are recommended to detect any adverse reactions or systemic effects associated with AgNPs. Additionally, further research is needed to elucidate the long-term effects of AgNPs exposure in orthodontic patients and establish guidelines for safe and responsible use.

Studies have indicated that when used in orthodontic applications, AgNPs exhibit antimicrobial properties without significant adverse effects on systemic health. However, it is crucial to note that the duration during which AgNPs maintain minimal or no effect on the patient’s systemic health may vary depending on factors such as the concentration of AgNPs, duration of exposure, and individual patient characteristics. Further research is needed to determine the long-term safety profile of AgNPs-coated orthodontic materials and establish guidelines for their safe use in clinical practice. Nanomaterials, especially silver nanoparticles, due to their size and concentration in the human body, can cause toxic effects, induce local inflammation and oxidative stress, and enter the circulatory system and consequently migrate to various organs, causing specific pathophysiological effects (eg, mitochondrial damage, DNA damage, necrosis, and even cell apoptosis) [30]. On the other hand, Ziaabka et al proved that the use of silver nanoparticles as active components in composite materials instead of conventional chemical products, such as ethanol or bleach, provided long-lasting bactericidal efficacy with no toxic effects. The authors showed that the assumed level of silver concentration (0.1 wt.%) in a middle ear implant revealed antibacterial efficacy, yet it was not toxic to animals and humans. Moreover, ex vivo evaluation of natissues implanted with prostheses modified with AgNPs revealed that the granulation tissue area around implants after 90 days of implantation was visibly smaller and was being replaced by the regenerating muscle tissue, suggesting that the presence of silver nanoparticles facilitated the healing process [32].

Strengths and Limitations

One strength of the present systematic review is its comprehensive analysis of diverse studies, encompassing various orthodontic materials and coating techniques. The inclusion of in vitro studies allowed for a focused assessment of the antimicrobial effects of silver coatings. The use of the Newcastle-Ottawa Scale for quality assessment adds rigor to the evaluation of study methodologies. Nonetheless, the diversity in study designs, methodologies, and outcome measures introduces a level of heterogeneity that may lead to variability in result interpretation and impose constraints on the generalizability of the findings. Additionally, the review primarily focuses on in vitro studies, and extrapolating these findings to clinical settings requires caution. Future research could address these limitations by using standardized methodologies and conducting well-designed clinical trials to validate the effectiveness of silver-coated orthodontic materials.

Conclusions

The present systematic review provides strong evidence supporting the antimicrobial efficacy of silver-coated orthodontic materials. The results may contribute to infection control measures in orthodontic practice, thus opening the way for further research and potential clinical applications of AgNPs. Ultimately, while AgNPs offer promising antimicrobial properties, their potential impact on patients’ health should be carefully considered and balanced with the need for effective infection control in orthodontic practice.