Access this article online
Quick Response Code:
Website:
www.jorthodsci.org
DOI:
10.4103/jos.jos_52_23

Metallurgy in orthodontic—A systematic review and meta-analysis on the types of metals used

Huda Abutayyem[1], Mohammad Khursheed Alam[2,3,4], Bushra Kanwal[5], Haytham Jamil Alswairki[6] and Yahya Abdullah Alogaibi[7]

[1]Department of Clinical Sciences, Center of Medical and Bio-Allied Health Sciences Research, College of Dentistry, Ajman University, Ajman, United Arab Emirates, [2]Orthodontic Division, Preventive Dentistry Department, Orthodontic Division, College of Dentistry, Jouf University, Sakaka 72345, Saudi Arabia, [3]Department of Dental Research Cell, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India, [4]Department of Public Health, Faculty of Allied Health Sciences, Daffodil International University, Dhaka, Bangladesh, [5]Specialist, Practicing in Dental Clinic, AlBaha, Saudi Arabia, [6]School of Dental Sciences, University Sains Malaysia, Gelugor 11800, Malaysia, [7]Consultant Orthodontist, Aseer Specialty Dental Center, Abha, Saudi Arabia

Address for correspondence:
Dr. Mohammad Khursheed Alam,
Orthodontic Division, Preventive Dentistry Department, Orthodontic Division, College of Dentistry, Jouf University, Sakaka 72345, Saudi Arabia.
E-mail: mkalam@ju.edu.sa
Huda Abutayyem and Mohammad Khursheed Alam – Joined 1st Author

Submitted: 10-Apr-2023
Revised: 27-Apr-2023
Accepted: 27-Apr-2023
Published: 04-Sep-2023

Abstract

A variety of metals and alloys are employed in the field of orthodontics, primary of which happen to be the construction of wires. Through this systematic review, we aimed to assess the various metallurgical characteristics of the said metals and alloys. Four hundred and eighty-two documents in total were found after a thorough search of the online journals, and 169 of the papers were initially chosen. Ultimately, 16 documents were selected that satisfied the necessary inclusion and exclusion criteria, primarily *in vitro* studies, literature reviews, and comparative analyses. NiTi alloy was found to be the most commonly used alloy in construction of orthodontic wires across all the studies that we had selected for our review. It also had better performance and consistency in terms of its usage as depicted by the meta-analysis performed, with stainless steel wires being a close second primarily due to its lesser cost compared to the former. Metallurgy and orthodontics are inextricably linked with one another. The various components of orthodontics such as wires, pliers, and other instruments utilize the metallurgical characteristics of metals and alloys that are specially prepared for the challenges of this field.

PROSPERO Registration Number: CRD42022378444.

Keywords:

Alloys, Metallurgy, Nickel-titanium, Orthodontic wires, Orthodontics

Introduction

Orthodontic archwires have evolved since they were first manufactured in the 1970s, becoming increasingly sophisticated and useful in a variety of clinical situations. The teeth are moved by the orthodontic archwires continuously and gently. The orthodontic archwire must exhibit elastic behavior when a force is applied over a few weeks to many months. Additionally, different orthodontic archwires are needed for the initial, intermediate, and ultimate phases of orthodontic therapy.[1,2]

Due to their special qualities—the shape memory effect and superelasticity—NiTi orthodontic archwires are the most often utilized archwires at the earliest stages of orthodontic treatment (leveling and alignment).[1-5] A martensitic transition is thought to have produced these functional characteristics. This transformation can be caused by heat or stress and can occur either directly from austenite (the parent phase with B2 cubic symmetry; space group) to martensite (the product phase with B19′ monoclinic symmetry; space group), or it can travel through the R-phase, an intermediary phase (trigonal symmetry; space group).[6]

Superelasticity is encouraged by stress-induced martensite (SIM), and the shape memory effect is encouraged by thermally induced martensite (TIM). Martensitic changes in NiTi alloys therefore

How to cite this article: Abutayyem H, Alam MK, Kanwal B, Alswairki HJ, Alogaibi YA. Metallurgy in orthodontic—A systematic review and meta-analysis on the types of metals used. J Orthodont Sci 2023;12:50.

Table 1: AMSTAR-2 16-point checklist of risk of bias assessment in studies selected for the systematic review

Studies selected	Question and inclusion	Protocol	Study design	Comprehensive search	Study selection	Data extraction	Excluded studies justification	Included study details
Bhagchandani *et al*. 2014[16]	Yes	Yes	Yes	Yes	Yes	No	No	No
Bhalekar *et al*. 2019[17]	Yes	Yes	Yes	Yes	Yes	No	No	No
Grygier *et al*. 2018[18]	Yes	Yes	Yes	Yes	Yes	No	No	No
Fernandes *et al*. 2011[19]	Yes	Yes	Yes	Yes	Yes	No	No	No
Freitas *et al*. 2011[20]	Yes	Yes	Yes	Yes	Yes	No	No	No
Gravina *et al*. 2014[21]	Yes	Yes	Yes	Yes	Yes	No	No	No
Łępicka *et al*. 2015[22]	Yes	Yes	Yes	Yes	Yes	No	No	No
Mesquita *et al*. 2018[23]	Yes	Yes	Yes	Yes	Yes	No	No	No
Mohammadi *et al*. 2014[24]	Yes	Yes	Yes	Yes	Yes	No	No	No
Muguruma *et al*. 2010[25]	Yes	Yes	Yes	Yes	Yes	No	No	No
Ntasi *et al*. 2013[26]	Yes	Yes	Yes	Yes	Yes	No	No	No
Sestini *et al*. 2006[27]	Yes	Yes	Yes	Yes	Yes	No	No	No
Sharma *et al*. 2017[28]	Yes	Yes	Yes	Yes	Yes	No	No	No
Shen *et al*. 2011[29]	Yes	Yes	Yes	Yes	Yes	No	No	No
Tian *et al*. 2017[30]	Yes	Yes	Yes	Yes	Yes	No	No	No
Vijayalakshmi *et al*. 2009[31]	Yes	Yes	Yes	Yes	Yes	No	No	No
Studies selected	**Risk of bias**	**Funding sources**	**Statistical methods**	**Risk of bias in meta-analysis**	**Risk of bias in individual studies**	**Explanation of heterogeneity**	**Publication bias**	**Conflict of interest**
Bhagchandani *et al*. 2014[16]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
Bhalekar *et al*. 2019[17]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
Grygier *et al*. 2018[18]	Yes	N/A	Yes	N/A	Yes	Yes	Yes	Yes
Fernandes *et al*. 2011[19]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
Freitas *et al*. 2011[20]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Gravina *et al*. 2014[21]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Łępicka *et al*. 2015[22]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
Mesquita *et al*. 2018[23]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
Mohammadi *et al*. 2014[24]	Yes	N/A	Yes	N/A	Yes	Yes	Yes	Yes
Muguruma *et al*. 2010[25]	Yes	N/A	Yes		Yes	Yes	Yes	Yes
Ntasi *et al*. 2013[26]	Yes	N/A	Yes		Yes	Yes	Yes	Yes
Sestini *et al*. 2006[27]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
Sharma *et al*. 2017[28]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
Shen *et al*. 2011[29]	Yes		Yes	Yes	Yes	Yes	Yes	Yes
Tian *et al*. 2017[30]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes
Vijayalakshmi *et al*. 2009[31]	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes

exhibit both thermal and mechanical hysteresis.[7] As is common knowledge, Ni content can regulate these practical qualities: Ti-rich NiTi alloys exhibit the form memory effect at room temperature, while Ni-rich and equiatomic NiTi alloys exhibit the superelastic effect close to and above it.

At a certain temperature, martensite (M) begins to develop as the material cools from the austenite (A) domain (M_s temperature). Direct transformation, which culminates at martensite finish temperature, is the process that converts austenite to martensite (M_f temperature). The austenite phase begins to form when the material in the low-temperature phase (M) is heated to a specific temperature; this value is known as the A_s temperature, and the transformation is complete when the A_f temperature is reached. Reverse transformation is the name given to this transition.[6]

As long as the martensitic stability temperature range is maintained, the material can sustain this deformation even when it is deformed in the martensitic domain up to a specific level (often up to 10%). When heated above A_s temperature, the material begins to take on its former shape. When A_f is reached, thermally induced martensite recovery by the shape memory effect ought to be complete.[6]

However, when a stress is applied to the material within a specific range of temperature where austenite is thermally stable, the stress-induced martensitic transformation takes place, which promotes the superelastic effect. After all applied stress has been removed, the deformation caused by loading may be recovered up to 10% strain.[6,8,9]

Orthodontic archwires made of ordinary superelastic NiTi exhibit a uniform composition all along the wire.

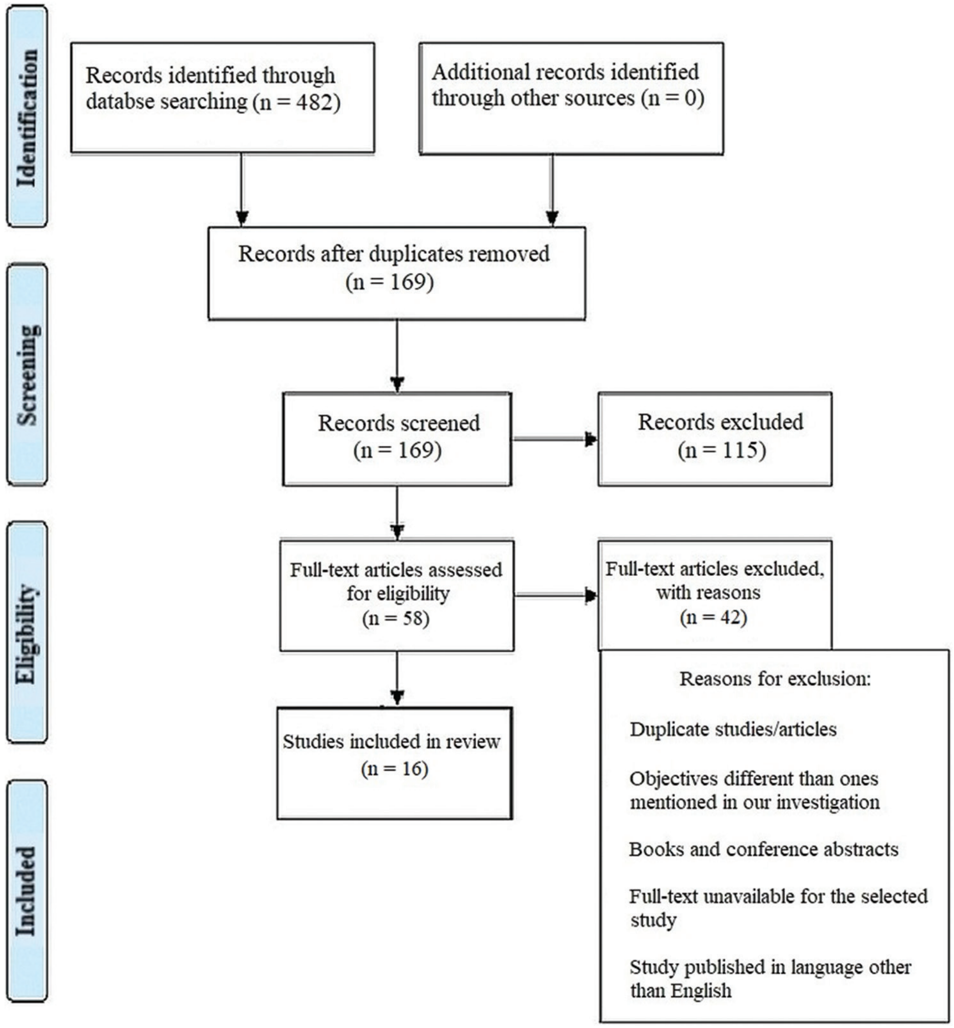

Figure 1: Representation of selection of articles through PRISMA framework

The forces necessary to move the incisor, premolar, and molar teeth, however, differ from one another. It is well known that a wire must have a structural gradient along its length to be subject to various actuating forces. By altering the Ni/Ti ratio in the austenite matrix, primarily through heat treatment, such as annealing, which encourages the Ni_4Ti_3 precipitate production, it is feasible to create this functional gradient. The range of transformation temperatures and the loading and unloading plateaus of the stress–strain curves during the superelastic regime are altered as a result of this precipitation, which also causes a local shift in the Ni/Ti ratio in the surrounding matrix.[6,10]

Some manufacturers use localized heat treatments to create this effect and make archwires that exhibit various actuation forces throughout the same archwire while taking into account the structural gradient.[11,12] Functionally graded materials have been employed for engineering applications in thermal, structural, optical, and electronic materials because of their high capacity for tackling complicated problems, such as those requiring a wider controllable range of temperature or stress.[13,14]

Hence, by the means of this systematic review and meta-analysis, we aimed to analyze studies available in orthodontic literature that mentioned the metallurgical characteristics of orthodontic wires and the various chemical, physiological, and physical interactions of the metals/alloys used in their construction (both inside and outside the oral cavity) as well as their performance compared to one another.

Materials and Methods

Protocol employed

This systematic review was performed as per the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) strategy and rules from the Cochrane group and the book Orderly Reviews in Health Care: Meta examination.

Review hypotheses

Through this systematic review, our primary objective was to review studies that were published in the orthodontic literature and that discussed the metallurgical properties of orthodontic wires, as well as the various chemical, physiological, and physical interactions of the metals and alloys used in their production (both inside and outside the oral cavity) and their performance in comparison with one another.

Study selection process

There were a total of 482 documents discovered after extensive search on the online journals, and 169 of the papers were selected initially. Following that, 115 similar/duplicate articles were eliminated, which resultantly made 58 separate papers available at first. The abstracts and titles of submissions were then reviewed, and a further 42 papers were eliminated. Finally, 16 documents that met the requisite inclusion and exclusion criteria were chosen, which primarily included *in vitro* studies, literature reviews, and comparative assessments [Figure 1].

Inclusion criterion

Articles that contained relevant data for our review objectives were selected for full-text screening. Studies that reported clinical trials, *in vitro* studies, randomized/non-randomized studies, systematic/literature reviews containing substantial sample volume, and detailed case reports were considered for inclusion in our review. We also monitored studies that possessed higher methodological quality.

Exclusion criteria

The following were excluded from the scope of our systematic review: incomplete data, seminar presentations, scholarly articles, placebo-controlled studies, and opinion articles.

Since the literature available on this topic was quite scant in volume, we did not limit our search in terms of the time period when the studies were published; that is, we took into account all the papers that were published in context to our topic (where the number of papers itself was found to be quite sparse in number). Also, excluded were literature reviews and cases published in languages other than English.

Search strategy

Using relevant keywords, reference searches, and citation searches, the databases PubMed-MEDLINE, Web of Science, Cochrane, and Scopus were all searched. “Alloys,” “metallurgy,” “nickel-titanium,” “orthodontics,” and “orthodontic wire” were the search terms used to access the database.

Data selection and coding

Two independent reviewers located the relevant papers by using the right keywords in various databases and online search tools. The chosen articles were compared, and a third reviewer was brought in if there was a dispute.

After choosing the articles, the same two reviewers independently extracted the following data: author, year of publication, country, kind of publication, study topic, population demographics (n, age), outcome measure(s), relevant result(s), and conclusion(s). The data were compared, and many differences were discussed with the third reviewer.

Risk of bias assessment

The AMSTAR-2 technique[15] was used to evaluate the risk of bias in the studies we chose. AMSTAR-2 joins a number of other instruments that have been released for this purpose as a critical evaluation tool for systematic reviews [Table 1]. As seen in Table 2 below, it is a 16-point checklist. Two instruments that have drawn a lot of attention served as the foundation for the creation of the original AMSTAR tool. The original AMSTAR was duplicated in two newly produced instruments. The AMSTAR-2 risk of bias items identifies the domains specified in the Cochrane risk of bias instruments for systematic reviews. In each case, these indicate an agreement that was achieved after input from more than 30 methodology experts.

Statistical analysis

After selecting data on the sample size, variables analyzed, and various elements of the investigations, the data were then entered into the Revman 5 program for meta-analysis. Forest plots illustrating the odds ratio for different study methodologies were obtained as part of the meta-analysis for our study as shown in Figures 2-5.

Results

The study design, methodology employed, description, and outcome are mentioned in Table 2. The results of the meta-analysis are provided in Figures 2-5.

Discussion

The pseudo-elasticity is enhanced, neighbor grain orientation is made easier with smaller grains, and the stiffness is correlated with the quantity of martensite plates created. According to the interaction between the transformational strain and each newly formed plate, these plates can be found in a variety of orientations.[32,33] Shape memory alloys (SMA) support pseudo-elastic and critical strain that is primarily caused by transformational strain, while superelastic unloading recovery is caused

Table 2: Description and outcomes as observed in the studies selected for the systematic review

Author and year of study	Study design	Study objective/description	Study inference/outcome
Bhagchandani *et al*. 2014[16]	*In vitro* study	The basic understanding of the micrograin structure of shape memory alloys used in orthodontics was the focus of this study. Archwires made of nickel-titanium and titanium molybdenum were chosen. The following tools were used to examine each sample's metallurgy: energy-dispersive X-ray spectroscopy with scanning electron microscopy.	While titanium molybdenum alloys displayed a very porous surface topography, nickel-titanium alloys displayed a highly rough surface with pits along with phases of intermetallic compounds of TiNi, Ni4Ti, and Ti2Ni. In both alloys, stabilizing element precipitates were visible at the grain boundaries. Equiatomic quantities of nickel and titanium were found in nickel-titanium alloys, with titanium somewhat higher than nickel. Interstitial elements with a high percentage, such as carbon and oxygen, were found; nevertheless, titanium molybdenum showed the highest percentage of titanium, followed by beta stabilizer, molybdenum, and interstitial elements with a low percentage.
Bhalekar *et al*. 2019[17]	*In vitro* study	A total of 20 metal orthodontic brackets (AO) were divided into ten groups and mixed with artificial saliva, coriander (*Coriandrum sativum*), turmeric (*Curcuma longa*), black pepper (*Piper nigrum*), red chili (*Capsicum annuum*), and salt to assess and compare *in vitro* corrosion of orthodontic metal brackets immersed in solutions of various spices and salt (sodium chloride) in this study. In a corrosion cell, the orthodontic brackets underwent electrochemical corrosion. Tafel analysis and potentiodynamic data were used to determine the corrosion current density (Icorr), corrosion potential (Ecorr), and pitting potential (Epit) rates.	The current investigation showed that salt, red chili, and black pepper were shown to increase corrosion, whereas turmeric and coriander exhibited reduced corrosion. Corrosion was seen to be worse in all salt-containing groups. Under a metallurgical microscope, surface analysis revealed that the coriander solution group had less pitting, while the red chili solution group had more.
Grygier *et al*. 2018[18]	*In vitro* study	The investigation of differences in the chosen structural qualities in relation to the corrosion resistance of the orthodontic wire material is the goal of the research that is provided in this work. The 0.016"x0.022" stainless steel edge arches supplied by two different vendors were the subject of the study. The investigation included an examination of the alloy under test's chemical and phase composition, microscopic examinations using techniques for light and electron microscopy, and electrochemical direct current measurements.	There were notable discrepancies between the structural and physical–chemical characteristics of orthodontic wires made of stainless steel of type 304 ALSI. The examined arches' chemical composition, metallurgical purity, phase composition, and corrosion resistance all differed significantly even though they were technically made from the same materials but by different producers. Additionally, it was noted that the evaluated materials did not conform to the mandatory normative standards for biomaterials in terms of structure.
Fernandes *et al*. 2011[19]	Literature review	To examine the shape memory effect and superelasticity of shape memory alloys, this study set out to understand the thermomechanical behavior of nickel-titanium (NiTi), a metal used in orthodontics, as well as its physical, mechanical, and metallurgical properties (SMAs).	The shape memory alloys (SMAs) made of nickel-titanium (NiTi) were employed in the production of orthodontic wires because of their superelasticity, high ductility, and corrosion resistance. When compared to stainless steel alloys, SMAs were shown to have higher strength and a lower elastic modulus. NiTi wires' pseudo-elastic property was enabled for dental displacements since they delivered light continuous forces over a larger range of deformation before returning to their original shape.
Freitas *et al*. 2011[20]	*In situ* study	The purpose of this study was to investigate the possibility that the silver solder used in orthodontics releases hazardous metallic ions into the saliva. Sixty youngsters between the ages of 8 and 14 made up the sample; 530 were divided into the control group and the study group (who required maxillary enlargement with the hyrax device). Saliva samples from each patient were taken six times from both groups—before the device was installed, 10 minutes, 24 h after, 7, 30, and 60 days later—to analyze the release of metallic ions. The amounts of cadmium, copper, zinc, and silver ions in saliva were measured using atomic absorption spectrophotometry in a graphite oven.	These ions were discharged in large quantities, with the highest concentrations occurring right after the appliance was installed. For cadmium, copper, and zinc, the ion concentrations in the control group had low values; for silver ions, the levels were not above the detection limit. Ten minutes after the appliance was placed, all ions in the study group displayed expressive concentrations, with copper and zinc having the highest and lowest means, respectively. Significant differences were seen between the groups when copper (all durations), zinc (10 minutes, 24 h, 7 and 30 days), and cadmium (only at 10 minutes) were compared.

Contd...

Table 2: Contd...

Author and year of study	Study design	Study objective/description	Study inference/outcome
Gravina *et al.* 2014[21]	Qualitative *in vitro* study	This study compared the surface morphology and qualitative chemical compositions of fracture regions in eight different types of nickel-titanium conventional wires, superelastic and heat-activated wires (GAC, TP, Ormco, Masel, Morelli, and Unitek), and copper-added wires (CuNiTi 27oC and 35oC, Ormco). The investigations were carried out using the EDS system of microanalysis and a scanning electronic microscope (energy-dispersive spectroscopy).	The findings demonstrated that Ni and Ti were the primary constituents of the alloy in NiTi wires, with little variation in their chemical makeup. However, the CuNiTi wires gave Ni and Ti a substantial amount of copper (Cu). In terms of surface morphology, the superelastic wires by Masel and Morelli had the lowest wire-surface roughness, whereas the CuNiTi wires by Ormco at 27°C and 35°C had the highest wire-surface roughness due to the presence of microcavities created by the pulling out of some particles, possibly NiTi. The fracture surfaces displayed microcavities and ductile fracture features. In terms of fracture, the heat-activated, superelastic, and CuNiTi 27oC wires by GAC and Unitek showed the lowest wire-surface roughness and smallest microcavities, whereas the CuNiTi 35oC wires showed insufficient wire-surface roughness.
Łępicka *et al.* 2015[22]	*In vitro*	The study's goal was to examine the corrosion damage to stainless steel fast palatal expansion Hyrax devices that had been silver-soldered. Useful in rapid palatal expansion (RPE) devices were examined macroscopically and in a scanning electron microscope with an energy X-ray analyzer for indications of corrosion after being used for 2 or 6 months, respectively.	The examined appliances revealed observable differences between the stainless steel components' and the noble solders' overall conditions. When compared to stainless steel wires, molar bands, and Hyrax screws, the surfaces of Ag-rich solders were primarily coated in corrosion pits. Additionally, the EDS examination revealed that the solders had a distinct element makeup. The findings show that noble materials, such as Ag-rich solders, can corrode when combined with stainless steel in a salivary environment.
Mesquita *et al.* 2018[23]	*In vitro* study	Ninety pairs of 0.018-in and 0.017–0.025-in NiTi wires were divided into three groups in this study based on the manufacturers, GI, GII, and GIII and were then electrically welded to determine the proper power level for welding three commercial brands of nickel-titanium (NiTi). Each group was broken down into smaller groups of five pairs of wires, where welding was carried out at various intensities. Power levels of 2.5, 3, 3.5, 4, 4.5, and 5 were employed in GI and GII and 2.5, 3, 3.5, and 4 in GIII (with each welding machine power level equaling 500W). The welded wire pairs were tested for tensile strength on a universal testing machine until they ruptured, at which point the maximum forces were noted.	While the 4.0 power offered the highest resistance in GI and GII (97.90N and 99.61N, respectively), the highest resistance in GIII (79.28N) was achieved with a 3.5 power welding. The 2.5 power demonstrated the lowest resistance to rupture in all groups (43.75N for GI, 28.41N for GII, and 47.57N for GIII).
Mohammadi *et al.* 2014[24]	Literature review	This paper's objectives were to study the metallurgy and crystal properties of NiTi alloy and to provide a broad overview of the existing articles on NiTi endodontic instrument surface treatment. A total of 176 articles were discovered, and the keywords associated with them were "endodontic treatment AND nickel-titanium," "electropolishing and NiTi rotary instruments," "thermal nitridation," "cryogenic treatment and nickel-titanium," and "plasma immersion ion implantation and nickel-titanium."	S1 files fared somewhat better after argon implantation, whereas nitrogen ion-implanted files performed worse during the fatigue test. Nitrogen ion implantation also lessened the cyclic wear on devices. The scientists also noted that cryogenic treatment improved the cutting efficiency, cyclic fatigue resistance, and microhardness of NiTi instruments and that thermal nitridation boosted the cutting efficiency and corrosion resistance of NiTi files in contact with NaOCl.
Muguruma *et al.* 2010[25]	*In vitro* study	This study's objectives were to examine the torsional characteristics of three experimental titanium miniscrew anchors for braces and to ascertain how these characteristics related to metallurgical structures. Ti-4Al-4V (duplex alpha-beta-titanium), Ti-33Nb-15Ta-6Zr, and commercially pure (CP) titanium (alpha-titanium) were used to make experimental miniscrew implants of 1.4 mm in diameter (beta-titanium). SEM was used to obtain the microstructures of etched cross-sections, and micro-X-ray diffraction (XRD) was used to detect phases (SEM).	The Ti-33Nb-15Ta-6Zr implant exhibited a significantly higher mean twist angle than the Ti-4Al-4V and Ti-33Nb-15Ta-6Zr implants at fracture, and both implants had significantly higher mean torques than the CP titanium implant. The Ti-33Nb-15Ta-6Zr and CP titanium implants demonstrated exceptional ductility and good fatigue performance. Ti-33Nb-15Ta-6Zr beta-titanium alloy has outstanding torsional characteristics, making it a good choice for making miniscrew implants.

Contd...

Table 2: Contd...

Author and year of study	Study design	Study objective/description	Study inference/outcome
Ntasi *et al*. 2013[26]	*In vitro* study	In this study, four modern Ag-based soldering alloys used to make orthodontic appliances, including Dentaurum Universal Silver Solder (DEN), Orthodontic Solders (LEO), Ortho Dental Universal Solder (NOB), and Silver Solder (ORT), were examined for their microstructure, hardness, and electrochemical behavior. For each alloy, five disk-shaped specimens were made, and after metallographic preparation, scanning electron microscopy with energy-dispersive X-ray (EDX) microanalysis, X-ray diffraction (XRD) analysis, and Vickers hardness testing were used to determine the microstructural characteristics, elemental composition, and hardness of the specimens.	The constituent composition, phase size and distribution, hardness, and electrochemical characteristics of Ag-based soldering alloys show wide variation. These variances may foreshadow changes in their clinical performance.
Sestini *et al*. 2006[27]	*In vitro* study	The authors looked at the connections made by electrical resistance welding, conventional soldering, and laser welding as well as two types of commercially available wires typically used for orthodontic appliances. These wires had similar chemical compositions (iron, carbon, silicon, chromium, molybdenum, phosphorus, sulfur, vanadium, and nitrogen), but different nickel and manganese contents. Using pure nickel- and chromium-plated titanium wires, the potential hazardous metals nickel and chromium were also investigated. To induce confluence, segments of each wire, cut into various lengths, were put to each well in which the cells were cultured. Alkaline phosphatase (ALP) activity was used to measure osteoblast differentiation, 3-(4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulphophenil)-2H-tetrazolium-phenazine ethosulfate method was used to measure fibroblast proliferation, and scanning electron microscopy (SEM) was used to measure keratinocyte viability.	Chromium significantly impacted fibroblast development. Both osteoblasts and fibroblasts were able to survive the joint created by electrical resistance welding, but traditional soldering significantly reduced both osteoblast alkaline phosphatase (ALP) activity and fibroblast viability and hindered the *in vitro* development of keratinocytes. Orthodontic wires with high nickel and chromium content hurt osteoblasts and fibroblasts but not keratinocytes.
Sharma *et al*. 2017[28]	*In vitro* study	The purpose of the study was to measure the levels of nickel in patient saliva over time. To do this, a total of twenty patients were used, ten of whom were bonded using standard 3M stainless steel brackets (group A) and ten of whom were bonded using nickel-free brackets (group B). On the basis of two separate manufacturing businesses, classic orthodontic and d-tech orthodontics, group B was further divided into two groups of five each. Each patient had three samples of stimulated saliva taken at three different times: before appliance implantation, an hour after appliance placement, and one week after appliance placement. An atomic absorption spectrophotometer was used to measure the amount of nickel released from the sample.	It was discovered that the nickel release in 3M stainless brackets during the first hour after bracket implantation was significantly higher than the nickel level before treatment. When the release was measured after one week, it was discovered that it had gradually decreased. The release of nickel steadily rose from the moment the appliance was put in the oral cavity over a period of one week in the second group, which included nickel-free brackets from classic orthodontics. The release of nickel from the third group's d-tech nickel-free orthodontic brackets was found to be significantly higher after one hour of appliance placement and to gradually decline over the course of one week. The study's conclusion was that manufacturing companies and extended time intervals have a significant impact on nickel release from simulated fixed orthodontic appliances.
Shen *et al*. 2011[29]	*In vitro* study	This research sought to investigate the microstructure and phase transition behavior of NiTi instruments made from a new controlled memory NiTi wire (CM wire). Differential scanning calorimetry (DSC) and x-ray diffraction were used in this work to investigate instruments of the brands EndoSequence (ES), ProFile (PF), ProFile Vortex (Vortex), Twisted Files (TF), Typhoon (TYP), and Typhoon CM (TYP CM), all size 25/.04. (XRD). Optical microscopy and scanning electron microscopy with x-ray energy-dispersive spectrometric (EDS) studies were used to examine the microstructures of etched instruments.	It was assessed that the austenite transition temperature is raised by the heat-treated TYP CM and Vortex instruments, and when compared to traditional superelastic NiTi instruments, the phase transformation behavior of the CM instrument has undergone considerable alterations. The DSC analyses revealed that each segment of the TYP CM and Vortex instruments had an austenite transformation completion or austenite-finish (Af) temperature greater than 37°C, in contrast to the NiTi instruments made from traditional superelastic NiTi wire (ES, PF, and TYP) and TF, which had Af temperatures significantly lower than mouth temperature.

Contd...

Table 2: Contd...

Author and year of study	Study design	Study objective/description	Study inference/outcome
			The austenite and martensite structure that was detected at room temperature with XRD was compatible with the higher Af temperature of TYP CM equipment. All NiTi instruments had martensite microstructures composed of colonies of lenticular features with significant twinning at normal temperature.
Tian *et al*. 2017[30]	*In vitro* study	In this study, neutron diffraction technology was used to perform quantitative metallurgical and phase investigations on two commercially available, rectangular austenitic stainless steel orthodontic archwires, measuring 0.43 mm and 0.64 mm (0.017 mm and 0.025 inch), respectively.	Results revealed a bi-phase structure with the predicted metastable austenite as well as a martensitic phase (45.67% for G&H and 6.62% for Azdent). The former, according to the researchers, may have resulted from a phase transformation caused by strain that developed during the cold working stage of wire manufacturing. In addition to the outcomes of conventional energy-dispersive X-ray spectroscopy, additional neutron resonance capture analysis determinations revealed atomic and isotopic compositions, including alloying elements in each sample. These findings together aided in connecting commercial alloying formulas and processing histories with specific mechanical performance, strength, and ductility.
Vijayalakshmi *et al*. 2009[31]	Comparative study	In this work, the mechanical and metallurgical characteristics of titanium molybdenum alloy (TMA) and stainless steel archwires were compared to those of newly developed titanium and titanium niobium archwires. Ten samples of archwires were divided into each of the four groups (groups I through IV). Tensile strength, yield strength, elastic modulus, load deflection, frictional qualities, and weld characteristics were all assessed.	Stainless steel was found to be the ideal material for both sliding and frictionless retraction mechanics due to its high strength, high stiffness, and low friction properties compared to other archwires. TMA is well suited to provide constant force in malaligned teeth due to its excellent formability, low stiffness, and low load deflection properties; nevertheless, high friction restricts its application in retraction to just loop mechanics. The scientists came to the conclusion that timolium can be used in practically all clinical scenarios since it has relatively low stiffness, superior strength, and behaves like a combination of stainless steel and TMA. The titanium-niobium archwire's low springback and great formability enable the production of finishing bends, making it suitable for use as a finishing archwire.

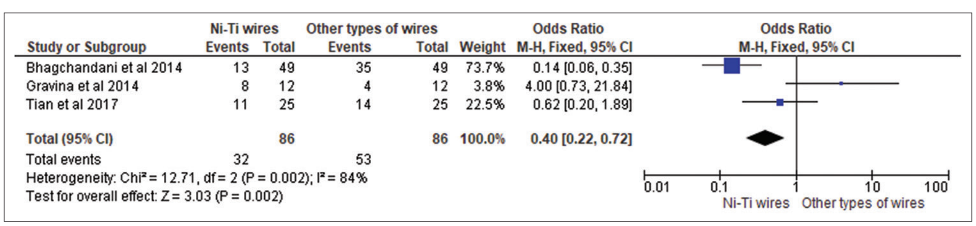

Figure 2: Odds ratio of *in vitro* studies selected in this systematic review which assessed the performance of NiTi wires represented on a forest plot after meta-analysis

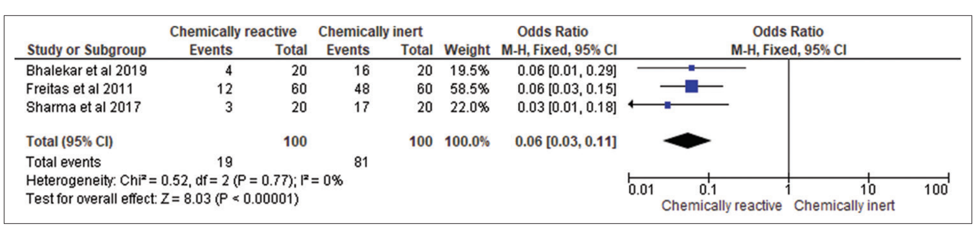

Figure 3: Odds ratio of *in vitro* studies selected in this systematic review where the metals/alloys were subjected to saliva, ordinary condiments, and corrosive liquids represented on a forest plot after meta-analysis

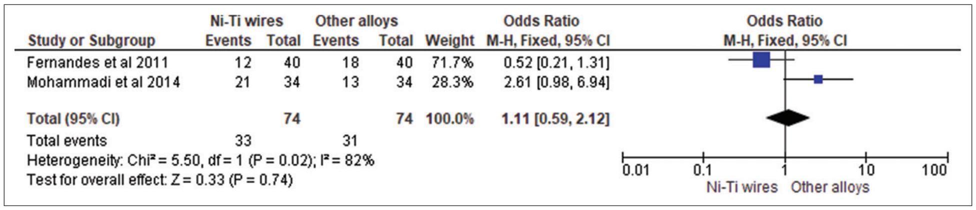

Figure 4: Odds ratio of literature reviews selected in this systematic review and their metallurgical analysis of orthodontic wires represented on a forest plot after meta-analysis

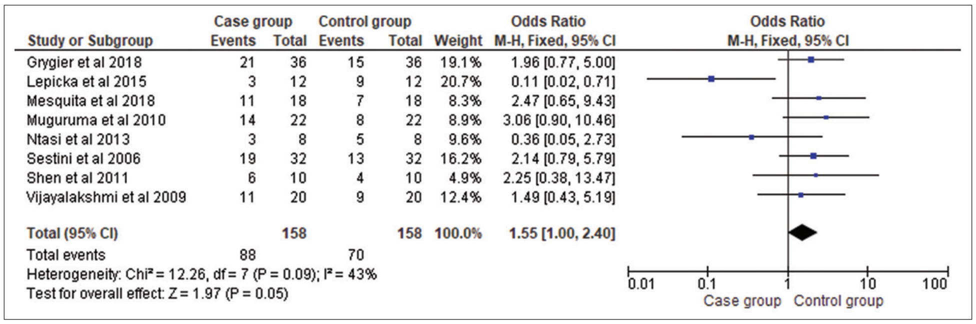

Figure 5: Odds ratio of comparative studies selected in this systematic review where the metals/alloys were compared in terms of their metallurgical profile against one another represented on a forest plot after meta-analysis

by the disappearance of martensite plates in conjunction with a decrease in transformational strain.[33] The range of transition temperatures and variations in the number of electrons accessible for bonding are both caused by the composition of NiTi alloys. The temperature of transformation (TTR) can be lowered, and the permanent yield strength of the austenite phase can be increased by about three times with a very modest excess of nickel in the structure. Additionally, it is possible to regulate the alloy's nickel content even during the melting and casting of ingots. In contrast, titanium-rich alloys have greater transformation temperatures than nickel less-rich or equiatomic NiTi alloys because they feature a second phase, Ti_2Ni, in their matrix.

In this systematic review, we assessed studies with different (but high-quality) methodological approaches to analyze various outcomes with respect to the metallurgical profiling of different types of metals/alloys used in the construction of orthodontic wires. For example, three of the studies that we selected in our review[17,20,28] analyzed the interactions of salivary fluids with the metals used in the orthodontic wires, and it was found that all the metals used in the wires interacted with the salivary constituents, indicating the potential hazards that can be associated with long-term usage of such appliances. These observations are similar to the investigations conducted by Babaei *et al*.,[34] where they had investigated potential hazards with respect to ions leaching in the oral cavity due to orthodontic appliance usage.

When the surface of wire was mechanically polished, Shabalovskaya[35] discovered that the Ti: Ni ratio was 5.5, indicating that there was five times as much Ti on the surface. The Ti: Ni ratio climbed to 23.4–33.1 and the Ni content reduced when the wire was autoclaved or brought to a boil in water. The Ti: Ni ratio in polished samples was 5.8, but after 30 days of immersion in a neutral electrolyte solution, it rose to 91. The titanium-aluminum vanadium alloy (Ti_6Al_4V) surface in the study by Hanawa *et al*.[36] had aluminum quantities comparable to the quantity of nickel in NiTi, despite the fact that Ti_6Al_4V's bulk material only contained 6% Al and NiTi had 50% Ni. On the surface of SS, Cr and Fe were detected in small concentrations, but Ni was absent.

One of the most biocompatible materials is pure titanium, as well as several of its alloys.[37] The stable titanium oxide layer is assumed to be responsible for their good biocompatibility. The oxide layer that forms on a titanium implant during implantation expands and absorbs minerals and other components of tissue fluids, and these reactions lead to surface modification. Hanawa[36] discovered that the calcium phosphate and titanium dioxide layers make up the oxide layer on the implants. In other words, a layer of inert oxide was covered in calcium phosphate. The Ca:P ratio of the film was similar to that of hydroxyapatite, and it was thicker on pure titanium than titanium alloys (including NiTi). Less hydroxyapatite-like calcium phosphates were produced on NiTi or Ti6Al4V. These results could have been influenced by the presence of Ni on the surface of NiTi alloy and aluminum on the surface of Ti6Al4V. This form of calcium phosphate layer is also present in SS. However, compared to NiTi, this layer forms more slowly.[36,38]

The corrosion resistance of Ti and related alloys in corrosive settings was increased by the TiN layer, as demonstrated by Shenhar *et al*.[39] and Huang *et al*.[40] According to Liu *et al*.,[41] nitriding NiTi instruments' surfaces at various temperatures improved their cutting effectiveness and corrosion resistance when they came into contact with sodium hypochlorite (NaOCl). According to a different investigation by Lin *et al*.,[30] adding a TiN layer to commercial rotary NiTi instruments at temperatures of 200°C, 250°C, and 300°C greatly improved the corrosion resistance of files in contact with 5.25% NaOCl. Despite the fact that the files nitrided at 300°C had the highest polarization resistance and lowest passive current, it is not advised to use this approach in clinical settings because at this temperature the instrument's superelasticity character may be lost. Therefore, for clinical use, equipment nitrided at 250°C is preferred.[41] Studies on the cryogenic treatment (CT) of NiTi rotary instruments are scarce. The effects of cryogenic treatment on the composition, microhardness, or cutting effectiveness of NiTi rotary instruments were examined by Kim *et al*.[42] They discovered that the microhardness of the cryogenically treated instruments was much higher than that of the controls. Additionally, the austenite phase was predominant in both the test and control groups, which were consisted of 56% wt Ni, 44% wt Ti, and 0% N. Deep dry CT greatly improved the cutting effectiveness of NiTi instruments, but it had little effect on wear resistance, according to a different study by Vinothkumar *et al*.[43] Deep CT considerably increased the cyclic fatigue resistance of NiTi rotary files, according to George *et al*.[44]

NiTi wires are manufactured using rolling and intermediate annealing techniques, which breaks the tiny crystal and necessitates recrystallization to produce predictable average grain size and orientation. Uniform grains or precipitates of some chemical components of the matrix may develop as a result of composition and thermal processing. These components, which have different properties from the matrix and are not thermodynamically stable at the heat treatment temperature, can be mixed with additional components and evenly distributed throughout the matrix. Precipitates of Ni2Ti and Ni3Ti allow more nickel to leave the crystal matrix, which lowers the Ni concentration and increases TTR. Other precipitates, such as Ti3Ni4, may have an impact on the mechanical properties of the matrix austenite phase, enhancing the shape memory effect's recoverability.[20,36]

Chemical metallurgy and physical metallurgy are two additional divisions of the vast and complex science of metallurgy. The reduction, oxidation, and chemical behavior of metals, mineral processing, metal extraction, thermodynamics, electrochemistry, chemical degradation, mechanical, physical, and performance characteristics of metals are only some of the major areas of study in metallurgical assessments. Further, crystallography, material characterization, mechanical metallurgy, phase transitions, and failure mechanisms constitute only a few of the practical applications of metallurgical sciences. Hence, we believe that the number of investigations that we selected for our systematic review and meta-analysis might be a little less than what would be considered ideal for a topic as boundless as metallurgy. However, we only selected studies that we deemed to have quite a high methodological quality and possessed results that were of a sound statistical value. We also ensured the selection of a variety of studies that carried different methodologies (*in vitro* studies, literature reviews, comparative assessments, part *in vivo* studies) which further reduced the ambiguity of the results that we obtained through the meta-analysis. However, it is imperative that more studies concerning the metallurgy of different metals and alloys be performed to keep pace with the rapidly evolving domain of orthodontics and ensure proper patient compliance in terms of both convenience and safety.

Conclusions

Metallurgy and orthodontics are inextricably linked with one another. The various components of orthodontics such as wires, pliers, and other instruments utilize the metallurgical characteristics of metals and alloys that are specially prepared for the challenges of this field. By the means of this systematic review, we shed light upon the different types of reactions that metals and alloys exhibit, in different solutions as well as compared to one another, and it was clear that among all the alloys utilized, NiTi was the most consistent in terms of its performance and consistency in usage.

Acknowledgements

The authors acknowledge the Saudi Orthodontic Society for their support.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. Melsen B, Cattaneo PM, Dalstra M, Kraft DC. The importance of force levels in relation to tooth movement. Semin Orthod 2007;13:220–33.
2. Proffit W, Fields H, Sarver D. Contemporary Orthodontics. 5th ed. St Louis: Elsevier Inc; 2013. doi: 10.1038/sj.bdj.2012.829.

3. Evans TJ, Durning P. Aligning archwires, the shape of things to come?--A fourth and fifth phase of force delivery. Br J Orthod 1996;23:269–75.
4. Antonucci V, Martone A. Phenomenology of Shape Memory Alloys, in: Shape Memory Alloy Engineering: For Aerospace, Structural and Biomedical Applications. Elsevier Inc; 2015. p. 33–56. doi: 10.1016/B978-0-08-099920-3.00002-4.
5. International Organization for Standardization. ISO 15841: Dentistry – Wires for Use in Orthodontics. Geneva: ISO; 2006., n.d. ISO 15841:2014-Dentistry -- Wires for use in orthodontics.
6. Otsuka K, Ren X. Physical metallurgy of Ti-Ni-based shape memory alloys. Prog Mater Sci 2005;50:511–678.
7. Frenzel J, George EP, Dlouhy A, Somsen C, Wagner MFX, Eggeler G. Influence of Ni on martensitic phase transformations in NiTi shape memory alloys. Acta Mater 2010;58:3444–58.
8. Ohara A. Clinial Importance of austenitic final point in the selection of nickel titanium alloys for application in orthodontic-use arches. Rev Odontológica Mex 2016;20:162–9.
9. Dentsply-GAC. Making a Good Use of a Good Material: BioForce ® Archwires. 2008. doi: 10.20081200020.
10. Shariat BS, Meng Q, Mahmud AS, Wu Z, Bakhtiari R, Zhang J, *et al*. Functionally graded shape memory alloys: Design, fabrication and experimental evaluation. Mater Des 2017;124:225–37.
11. Fernandes F M, Camacho E, Rodrigues PF, Inácio P, Santos TG, Schell N. *In situ* structural characterization of functionally graded Ni–Ti shape memory alloy during tensile loading. Shape Mem Superelasticity 2019;5:457–67.
12. Karami B, Janghorban M, Tounsi A. Novel study on functionally graded anisotropic doubly curved nanoshells. Eur Phys J Plus 2020;135:1–31.
13. Bataillard L, Bidaux JE, Gotthard R. Interaction between microstructure and multiple-step transformation in binary NiTi alloys using in-situ transmission electron microscopy observations. Philos Mag A Phys Condens Matter Struct Defects Mech Prop 1998;78:327–44.
14. Miyamoto Y, Kaysser WA, Rabin BH, Kawasaki A, Ford RG. Applications in: Functionally Graded Materials. Boston, 1999. p. 247–313. doi: 10.1007/978-1-4615-5301-4_7.
15. Shea BJ, Reeves BC, Wells G, Thuku M, Hamel C, Moran J, *et al*. AMSTAR 2: A critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. BMJ 2017;j4008. doi: 10.1136/bmj.j4008.
16. Bhagchandani J, Loomba A, Loomba K, Singh AK. Microscopic grain structure analysis of titanium-based orthodontic archwires. J Indian Orthod Soc 2014;48:168–74.
17. Bhalekar BH, Nanjannawar LG, Agrawal JM, Fulari SG, Shetti SS, Kagi VA, *et al*. Corrosion of orthodontic brackets immersed in spices and salt solution: A pilot study. J Clin Diag Res 2019;13. doi: 10.7860/jcdr/2019/41762.13343.
18. Grygier D, Hoppe V, Zięty A, Rutkowska-Gorczyca M. Evaluation of the differentiation of structural and physicochemical properties of orthodontic wires of AISI 304 stainless steel. Eng Biomater 2018;21:8-13.
19. Fernandes DJ, Peres RV, Mendes AM, Elias CN. Understanding the shape-memory alloys used in orthodontics. ISRN Dent 2011;2011:132408.
20. Freitas MP, Oshima HM, Menezes LM. Release of toxic ions from silver solder used in orthodontics: An in-situ evaluation. Am J Orthod Dentofacial Orthop 2011;140:177–81.
21. Gravina MA, Canavarro C, Elias CN, das Graças Afonso Miranda Chaves M, Brunharo IH, Quintão CC. Mechanical properties of NiTi and CuNiTi wires used in orthodontic treatment. Part 2: Microscopic surface appraisal and metallurgical characteristics. Dental Press J Orthod 2014;19:69–76.
22. Łępicka M, Grądzka-Dahlke M, Szarmach I. Corrosion damage investigation of silver-soldered stainless steel orthodontic appliances used in vivo/Ocena Zniszczeń Korozyjnych Używanych *In Vivo* Stałych Aparatów Ortodontycznych O Połączeniach Lutowanych Na Bazie Srebra. Arch Metall Mater 2015;60:2569–72.
23. Mesquita TR, Martins LP, Martins RP. Welding strength of NiTi wires. Dental Press J Orthod 2018;23:58–62.
24. Mohammadi Z, Soltani MK, Shalavi S, Asgary S. A review of the various surface treatments of NiTi instruments. Iran Endod J 2014;9:235-40.
25. Muguruma T, Iijima M, Brantley WA, Yuasa T, Ohno H, Mizoguchi I. Relationship between the metallurgical structure of experimental titanium miniscrew implants and their torsional properties. Eur J Orthod 2010;33:293–7.
26. Ntasi A, Jabbari YA, Mueller WD, Eliades G, Zinelis S. Metallurgical and electrochemical characterization of contemporary silver-based soldering alloys. Angle Orthod 2013;84:508–15.
27. Sestini S, Notarantonio L, Cerboni B, Alessandrini C, Fimiani M, Nannelli P, *et al*. *In vitro* toxicity evaluation of silver soldering, electrical resistance, and laser welding of orthodontic wires. Eur J Orthod 2006;28:567–72.
28. Sharma RK, Malik A, Gupta A, Nabhi K, Sharma D, Evaluations of saliva for nickel release from conventional stainless steel and nickel free orthodontic brackets- An Atomic Absorption Spectrophotometric (AAS) study. IP Indian J Orthod Dentofacial Res 2017;3:98-102.
29. Shen Y, Zhou HM, Zheng YF, Campbell L, Peng B, Haapasalo M. Metallurgical characterization of controlled memory wire nickel-titanium rotary instruments. J Endod 2011;37:1566-71.
30. Tian KV, Festa G, Basoli F, Laganà G, Scherillo A, Andreani C, *et al*. Orthodontic archwire composition and phase analyses by neutron spectroscopy. Dental Mater J 2017;36:282–8.
31. Vijayalakshmi R, Nagachandran K, Kummi P, Jayakumar P. A comparative evaluation of metallurgical properties of stainless steel and TMA archwires with timolium and titanium niobium archwires – An *in vitro* study. Indian J Dental Res 2009;20:448.
32. Pattabi M, Ramakrishna K, Mahesh K. Corrigendum to "Effect of thermal cycling on the shape memory transformation behavior of NiTi alloy: Powder X-ray diffraction study". Mater Sci Eng A 2009;448:33–8.
33. Nygårds M. Number of grains necessary to homogenize elastic materials with cubic symmetry. Mech Mater 2003;35:1049-57.
34. Babaei Hatkehlouei M, Dadgar S, Shokrzadeh M, Mousavi J, Sobouti F. A review of the requirements and hazards of toxic metals from orthodontic wires. Pharm Biomed Res 2021;6:251-60.
35. Shabalovskaya SA. On the nature of the biocompatibility and on medical applications of NiTi shape memory and superelastic alloys. Biomed Mater Eng 1996;6:267-89.
36. Hanawa T, Hiromoto S, Asami K, Okuno O, Asaoka K. Surface oxide films on titanium alloys regenerated in Hanks' Solution. Mater Trans 2002;43:3000-4.
37. Vadiraj A, Kamaraj M. Effect of surface treatments on fretting fatigue damage of biomedical titanium alloys. Tribol Int 2007;40:82-8.
38. Hanawa T, Asami K, Asaoka K. Repassivation of titanium and surface oxide film regenerated in simulated bioliquid. J Biomed Mater Res 1998;40:530-8.
39. Shenhar A, Gotman I, Radin S, Ducheyne P. Microstructure and fretting behavior of hard tin-based coatings on surgical titanium alloys. Ceram Int 2000;26:709-13.
40. Huang H, Hsu C, Pan S, He J, Chen C, Lee T. Corrosion and cell adhesion behavior of tin-coated and ion-nitrided titanium for dental applications. Appl Surf Sci 2005;244:252-6.
41. Liu J, Lin M, Hsu M, Li U, Lin C, Tsai W, *et al*. Effect of nitriding surface treatment on the corrosion resistance of dental nickel–titanium files in 5.25% sodium hypochlorite solution. J Alloys Compd 2009;475:789-93.

42. Kim JW, Griggs JA, Regan JD, Ellis RA, Cai Z. Effect of cryogenic treatment on nickel-titanium endodontic instruments. Int Endod J 2005;38:364-71.
43. Vinothkumar TS, Miglani R, Lakshminarayananan L. Influence of deep dry cryogenic treatment on cutting efficiency and wear resistance of nickel–titanium rotary Endodontic instruments. J Endod 2007;33:1355-8.
44. George G, Sekar M, Sanjeev K. An *in vitro* evaluation of the effect of deep dry cryotreatment on the cutting efficiency of three rotary nickel titanium instruments. J Conserv Dent 2011;14:169.