

Orthodontic Biomaterials: From the Past to the Present

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“Men will never barter their souls or spill blood for it; yet this time-tested stainless steel, with the single exception of intrinsic value, offers more desirable characteristics to the fine-metal worker than do the precious metals themselves. The craftsman asks only that his material be chemically inert, naturally beautiful, strong yet amenable to his artistry; it is the buyer who measures precious metals by price.” (Commercial advertisement touting stainless steel [ca 1935]¹)

FOREWORD

Like metallurgy, dentistry has a long history of artistic creativity. Over 4500 years ago when the metal worker was sweating copper from malachite for weapons, making primitive tools from “bia’ n pet” (meteoric iron), and separating gold from crushed quartz stone literally using what became known as the Golden Fleece,^{2,3} the “Toother” was likely splinting the teeth of the Egyptian court.^{4,5} Time passed from the Bronze Age to the Iron Age and the Industrial Revolution until, in the latter half of the 19th century, Henry Clifton Sorby^{6,7} (1863–1887) and Edward Hartley Angle⁸ (1886–1930) professionally ascended to become the pioneers of modern metallography and modern orthodontics, respectively. Yet from all these artistic developments, the formalized scientific understanding of both fields was limited to about the last 100 years. This series of three articles traces the evolution, development, and characteristics of orthodontic materials from the first applications from the past to the present; the research developments on composites, titanium, and low-friction materials from the present to the immediate future; and the changing paradigm of tooth mo-

bility and its associated roles in biotechnology, genomic advances, nanotechnology, and simulated chemistry from the immediate future and beyond. In this first article of the series, let us now explore the fascinating chronology of “Orthodontic Biomaterials: From the Past to the Present.”

THE BEGINNINGS

Teeth were regarded by the ancients as very precious to the extent that “. . . special penalties [were exacted] for knocking out the teeth of an individual, either freeman or slave.”⁹ As early as 400 BC, Hippocrates referenced in his writings the correction of tooth irregularities.¹⁰ And while Greece was in its Golden Age, the Etruscans (the precursors of the Romans) were burying their dead with appliances that were used to maintain space and prevent collapse of the dentition during life.^{11,12} Then in a Roman tomb in Egypt, Breccia finds a number of teeth bound with a gold wire,¹³ and at the time of Christ, Aurelius Cornelius Celsus first records the treatment of teeth by finger pressure.¹² Thus, inherent malocclusions and the use of corrective forces are recognized, the virtue of maintaining space is appreciated, and the first orthodontic material is documented—a gold ligature wire.

EARLY CONTRIBUTORS

The French and English dominated the earliest contributions to the field of orthodontics, which as yet had not been formally named. Among these contributors is Fauchard (1723) who invents the expansion arch and gives the first comprehensive discussion of appliances.¹⁴ The reputed father of dentistry details the use of ligature wires and gold or silver mechanical devices. He corrects teeth using finger pressure and silk thread and intuitively recognizes that the source of a force does not matter in mechanotherapy.

In 1819 Delabarre introduces the wire crib, and this marks the birth of contemporary orthodontics.¹⁵ Later, Schangé¹⁶ would show that the gold wire crib afforded adequate anchorage and formed a base for attachments.¹² A century later, Lufkin¹⁷ would state that “. . . Schangé made an invaluable contribution” because it really marked the beginning of edgewise. In the second half of the 19th century (ca 1865), Kingsley advocates plates as retaining devices. In the early part of the 20th century, Angle would tout this device as one of the best tooth maintainers.¹⁸ Fifteen years later, Kingsley would write his book, “Oral De-

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TABLE 1. Compositions of Alloys Used During the 20th Century

Material	Range of Compositions (weight %)
Brass ²³	65–88Cu, 12–35Zn
14- to 18-karat Gold ^{24–26}	58–75Au, 7–18Cu, 10–26Ag, 1–10Pd ^a , 5–25Pt ^a , 0–19Ir ^a , 1–2Ni
Nickel silver ^{22,23}	47–65Cu, 10–25Ni, 15–42Zn, 0–1Pb
Stainless steel ^{26,27}	45–84Fe, 8–30Cr, 8–25Ni, 0.1–0.2C
Cobalt chromium ²⁸	40Co, 20Cr, 16Fe, 15Ni, 7Mo, 2Mn, 0.15C, 0.04Be
CP-titanium ^{b 29–31}	99Ti, <0.10C, <0.50Fe, <0.06H, <0.40N, <0.40O
($\alpha + \beta$) Ti ^{29–32}	88–91Ti, 5–7Al, 3–5V
NiTi-M ^{c 33–35}	44–52Ni, 45–51Ti, 5–6Cu, 0.2–0.5Cr, 0–3Co
NiTi-A ^{d 33–35}	44–52Ni, 45–51Ti, 5–6Cu, 0.2–0.5Cr, 0–3Co
β -Titanium ^{30–32}	76–82Ti, 10–12Mo, 5–7Zr, 3–5Sn
Titanium-niobium ^{e 36,37}	51Ti, 49Nb

^a In 1933 these three elements could constitute 25% of an alloy.²⁶

^b CP-titanium denotes a commercially pure titanium alloy.

^c NiTi-M denotes the martensitic or low temperature phase of nickel-titanium alloys.

^d NiTi-A denotes the austenitic or high temperature phase of nickel-titanium alloys.

^e F. Farzin-Nia, personal communication.

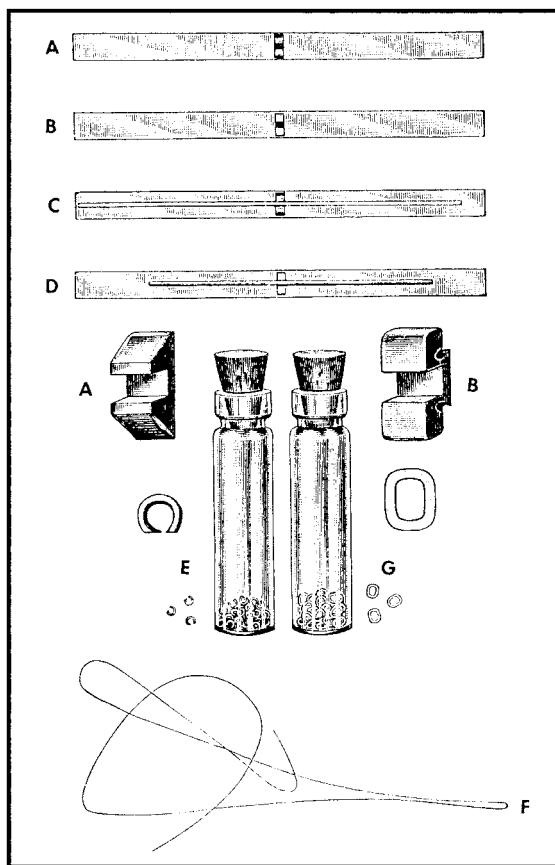


FIGURE 1. Edgewise paraphernalia of ca 1928.⁶⁴ (A) The wingless bracket on and off a band strip; (B) the prototype of the modern bracket on and off a band strip; (C) A with an archwire engaged; (D) B with an archwire engaged; (E) various types of staples; (F) a ligature wire; and (G) threaded washers, which were used as spacers.

formities,” which would become the most comprehensive text on the subject in its day.¹⁷ In 1877, Johnston would recommend placing zinc in a predrilled hole of a steel jack-screw, which was simultaneously invented by Dwinelle and Gaine (ca 1849), to “. . . give it the same immunity from oxidation as gold or platinum.”¹² Modern textbooks term this the concept of the ‘sacrificial anode.’¹⁹

THE ENLIGHTENMENT

No matter how some of his contemporaries personally felt about Edward Angle, there is no question that he dominated this era. In 1908, Norman William Kingsley already called Angle “. . . one of the greatest empirics of his day.”²⁰ Angle identified and lauded many people who sought the truth—Fauchard, Fox, Harris, Kingsley, Magill, Schangé, and Wescott;²¹ he also criticized and wrote scathing letters to those he thought were poisoning the newly formed practice of “orthodontia” as it was called in 1917. He particularly admired Kingsley who, like Farrar (1926), was hailed by his contemporaries as “the father of orthodontia.” Kingsley made particularly substantive contributions to our knowledge of occipital anchorage, which in that period would have been constructed using elastic straps, forged Stubbs’ steel, and a swaged silver plate.^{18,20,21}

On the other hand, a material was the proximate cause of the rift between those who used heavy and bulky nickel-silver appliances (the German School) and Edward Angle and his contemporaries.²¹ In 1906, Angle and most of his graduates resigned from The Society, in part because of their difference toward nickel-silver alloys (ie, German silver or “Neusilber”), which were first introduced by Angle to the United States in 1887²⁰ but which were actually copper, nickel, and zinc alloys that contained no silver²² (Table 1). During this period, gold, platinum, silver, steel, gum rubber, vulcanite and, occasionally, wood, ivory, zinc, and copper were used as was brass in the form of loops, hooks,

TABLE 2. Reported Properties of Alloys Used During the 20th Century

Material	Young's Modulus, (GPa)	Yield Strength, (MPa)	Tensile Strength, (MPa)
Brass ^{23,41}	100–120	70–460	260–900
14- to 18-karat Gold ^{24,25,42–45}	85–110	170–570	320–1120
Nickel silver ^{22,23}	120	140–540	390–640
Stainless steel ^{27,29,46–49}	180–220	790–2450	930–2860
Cobalt chromium ^{29,46,49–52}	180–230	960–2140	1210–2540
CP-titanium ^{29–31}	100–110	170–1000	240–1100
($\alpha + \beta$) Ti ^{29–32}	100–120	740–1130	860–1220
NiTi-M ^{35,46,47,53–58}	28–44	70–1240	900–1930
NiTi-A ^{35,47,53}	80–110 (32–60) ^a	180–690 (460–1590) ^b	800–1670
β -Titanium ^{30,31,46,54,56,57,61}	65–70 ^c	520–1380	690–1500
Titanium-niobium ^{d 48}	65–93	760–930	900–1030

^a Although $E_{\text{NiTi-A}}$ (E is the Young's modulus) should be as much as four times greater than $E_{\text{NiTi-M}}$ ^{59,60}, recent experiments show that heavily drawn orthodontic wires have a considerably lower $E_{\text{NiTi-A}}$ ⁴⁷ perhaps suggesting that both phases (NiTi-M and NiTi-A) are present.

^b Because yield points do not accurately predict the behavior of NiTi-A alloys, elastic limits are reported that were obtained from cyclic loading tests.⁴⁷

^c The Young's moduli of these alloys can increase to 100 GPa but only if they are properly aged at 480–595°C (900–1100°F) for 8.0–32 hours after solution treatment at 690–790°C (1275–1450°F) for 0.13–1.0 hours.^{32,40,62}

^d F. Farzin-Nia, personal communication.

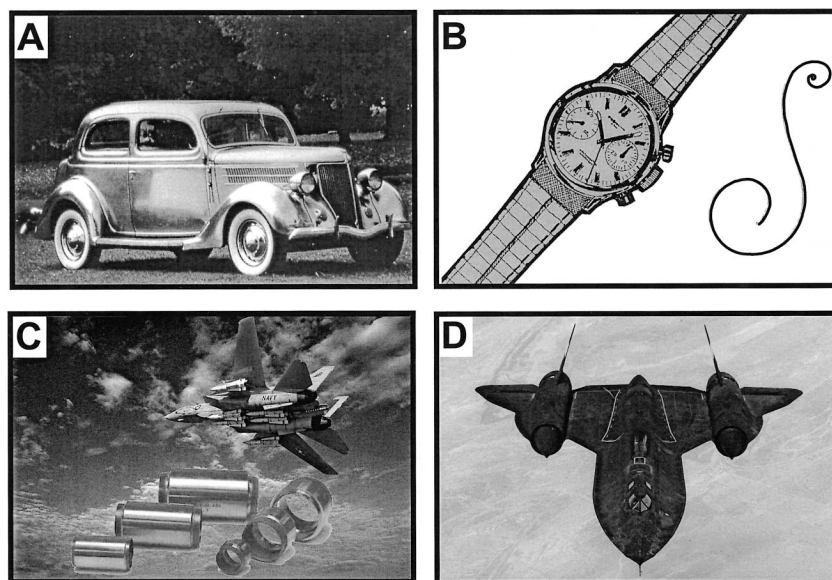


FIGURE 2. Products made from alloys that orthodontics adopted. (A) 1936 Ford sedan made from stainless steel;⁷⁵ (B) mainspring of a watch fabricated from cobalt-chromium alloy;⁵⁰ (C) hydraulic shape-memory coupling manufactured from nickel-titanium intermetallic composition;^{76,77} and (D) SR-71 Blackbird constructed from titanium-molybdenum alloy.⁷⁸

spurs, and ligatures.^{12,20} Fourteen- to 18-karat gold was routinely used for wires, bands, clasps, ligatures, and spurs,³⁸ as were iridium-platinum bands and archwires¹ and platinumized gold for brackets.³⁹ The advantage of gold was that you could heat treat it to variable stiffnesses (30%), which was comparable to today's beta-titanium alloy^{24,40} (Table 2). This was accomplished by heating at 450°C (842°F) for 2 minutes, cooling to 250°C (482°F) over a period of 30 minutes, and finally quenching to room temperature.^{26,63} Gold had excellent corrosion resistance too. In 1920, Dewey presents a paper on the clock spring auxiliary as an "Application of Spring Forces from Gold and Platinum Removable Appliances."^{18,21} This presentation was credited as be-

ing the long-awaited response to the nickel-silver appliances that caused the rift 14 years earlier.

Finally, in the Dental Cosmos (1928), we see the design of what was to become known as the edgewise appliance (Figure 1),⁶⁴ which was never formally named by Edward Angle in his lifetime.⁶⁵ On August 11, 1930, Edward Angle passed into history. As a tribute to him, we should recognize that in a 40-year career, he truly did understand patients and their tissues, had knowledge of biology and engineering, comprehended mechanical requirements, and contributed four distinct biomechanical appliances⁶⁵—the Angle E arch, the pin and tube appliance, the ribbon arch, and the edgewise appliance.³⁸ No one has yet eclipsed those

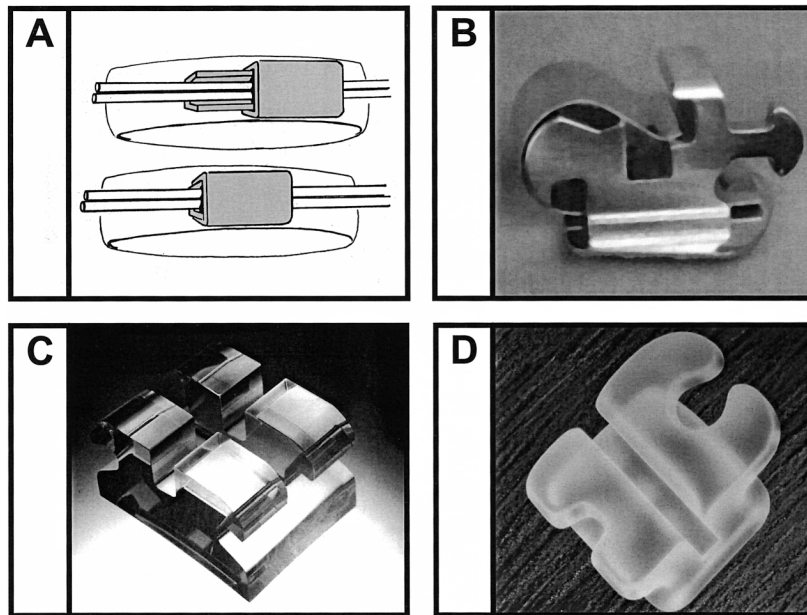


FIGURE 3. Some premier brackets of the 20th century. (A) The gold or chromium alloy Johnson friction cap;^{21,90} (B) a SPEED[®] self-ligating stainless steel bracket;⁹¹ (C) the Starfire[®] single-crystal sapphire bracket;⁹² and (D) an Allure[®] polycrystalline alumina bracket.⁹³

accomplishments. One could readily argue that Edward Angle was one of the first biomedical engineers. Yet with all these accomplishments, Angle was not the great innovator of novel materials—others would fulfill that role.

STAGNATION ABOUNDS

From the 1930s to the 1960s, the proliferation of materials did not occur. With the death of Edward Angle, a time of stagnation eventuates. As Thurow said, “. . . the ‘edge-wise men’ literally rode off in all directions at once.”⁶⁵ What became more important at that time because of their lack of development were cephalometrics and biological aspects.^{65,66} And so for a while, those fields of knowledge were emphasized, as profound changes to orthodontics occurred at the expense of novel materials and innovative mechanics. It is during this period that Begg gives this warning to the orthodontic community: “Orthodontics is ill-served by presentation of new orthodontic techniques that are claimed to be based on adaptations of engineering principles but that have not been proven suitable for successful treatment of patients.”⁶⁷ We should not forget that Cassandra-like quote because, later on, as a period of proliferation yields to one of consolidation, many materials that would be offered to the practitioner would be retracted either because they were not effective as engineering materials or because they had other clinical shortcomings.

During this materials stagnation, we learn that gold alloys have deficiencies too. At the 1931 meeting of the American Association of Orthodontists (AAO), Norris Taylor and George Paffenbarger discussed wrought alloys and intimated that more springiness and fewer cracks at tension

points were possible.²¹ And at nominally \$30 per ounce, Kelsey said that they were costly. Little did they know that the cost of gold would spike to nearly \$900 in early 1980!⁶⁸

By the early 1930s, stainless steels were generally available. Although Dumas, Guillet, and Portevin first made stainless steel in France, its “stainless” qualities were first reported in Germany by Monnartz also around 1900–1910.⁶⁹ Stainless steel languished until World War I spurred the development of three different kinds of stainless steels, and ironically those developers received the credit for the discovery. During that war, the Germans, British, and Americans developed an austenitic, a martensitic, and a ferritic stainless steel, respectively.⁷⁰ Actually 6 years before Edward Angle expired, Dr Lucien DeCoster of Belgium was experimenting with “rustless” steel.⁷¹ In the West and Southwest, Carman, Walsh, Bell, and others experimented with stainless steel and cobalt-chromium alloys,²¹ the latter of which paralleled the work on Vitallium (1927) by Venable and Stuck at Howmedica’s Austenal Labs.^{72,73} Half a world away, Begg started fabricating 0.457 mm (0.018-inch) round stainless steel wires with vertical loops and intermaxillary hooks.³⁹ In the early 1940s, Begg would partner with Wilcox to make what they envisioned to be the ultimate in resilient orthodontic wires—Australian stainless steels. Yet, it was not until about 1960 that stainless steel was generally accepted. Nonetheless, in 1933 we find that stainless steel and a chromium alloy are being used, as Archie Brusse (the founder of Rocky Mountain Metal Products) gives a table clinic on the first complete stainless steel system at the American Society of Orthodontists (ASO) in Oklahoma City⁷⁴—and so the struggle

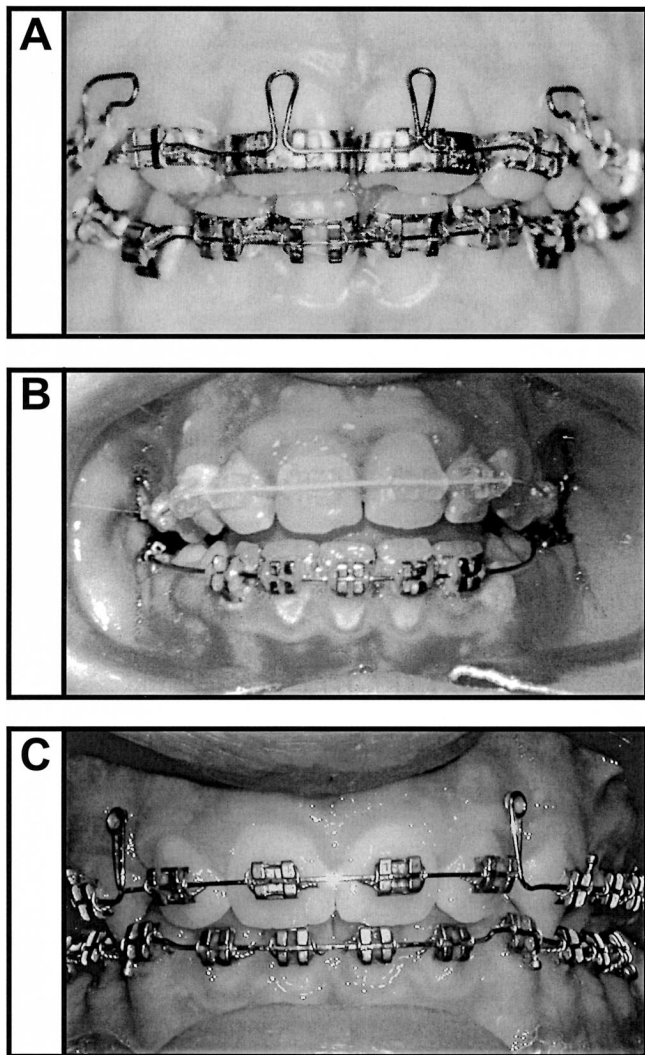


FIGURE 4. Orthodontic cases from yesteryear to today. (A) A fully banded patient with extensive stainless steel (SS) loop mechanics, ca 1965;⁶⁵ (B) a patient fitted with maxillary polycarbonate brackets and a Teflon[®]-coated SS archwire and mandibular SS conventional brackets, ca 1980; and (C) a patient with conventional straight-wire CP-titanium brackets, ca 1995 (F. Sernetz, personal communication).

between gold and stainless steel formally begins. For a time, the automotive manufacturers even got involved. In 1936, the Ford Motor Company made six prototype stainless steel sedans and drove them over 320,000 km (200,000 miles)(Figure 2A).⁷⁵ When they were restored at the end of the 20th century, every piece of plain carbon steel had to be replaced except for their bodies, which were still gleaming. Just a year earlier (1935), Stolzenberg reports on the first ligatureless edgewise bracket—the Russell Lock appliance.^{79,80} This bracket purports some distinct advantages; ie, by a screw device, the clearance can be continuously adjusted from its minimal friction to infinite friction. In 1942, George Herbert speaks on materials at the AAO meeting on materials about “Fabricating of Chrome Alloys

in Different Types of Treatment Appliances”—and the controversy heats up.

Regarding acrylics, unaesthetic vulcanite plates with 1.02 mm (0.040-inch) resilient gold wires were replaced by translucent acrylic plates soon after acrylic’s discovery in 1937.^{18,42,81} Vulcanite was a vulcanized (cross-linked) natural rubber product that was developed by Nelson Goodyear in 1851 and patented for dental plates in 1855.⁸¹ In the 1880s, Keely was correcting misplaced teeth with black Vulcanite plates having jack screws and “well-seasoned” pins of pine.²⁰ Hawley offered such appliances a few years after they were exhibited by others at the 1912 Eastern Association of the Graduates of the Angle School of Orthodontics.¹⁸ Although cellulose, phenol-formaldehyde, vinyl polymers and copolymers, styrene, and alkyd resins were explored,⁸² by the 1940s, acrylic materials were being polymerized into plates by reacting, under heat and pressure, doughs made from methyl methacrylate monomer and acrylic powder, the latter of which reduced shrinkage.^{42,83} Later, self-curing acrylics would be made by adding an accelerator to the initiator that creates free radicals^{42,81} in order to hasten the Trommsdorff gel effect.⁸⁴ In World War II, acrylic would be used as the cockpit canopy in aircraft because of its transparent qualities.^{85,86} Only after pilots were injured as a result of projected chards of the acrylic, would physicians also learn of its relative bioinertness.⁸⁷ Ultimately, acrylic was so successful that, by 1946, 98% of all denture bases were constructed of this polymer or its copolymers.⁸¹ Today acrylic is the most frequently used material for retainers—whether they be a Hawley or a lingual wire-retaining device, the latter of which was first fabricated in 0.762 mm (0.030-inch) gold wire using bands with lingual spurs and hooks.¹⁸ What Kingsley (1908) said almost 100 years ago still rings true today—that “. . . the success of orthodontia as a science and an art now lies in the retainer.”²⁰

Now we arrive at a very interesting point in history—“The Edgewater” tradition. The Edgewater Beach Hotel in Chicago was a site of many AAO Meetings. If its walls still stood, it would tell many stories about materials in orthodontics that transpired during those meetings of the 1930s, 1940s, and 1950s. One notable meeting occurred in 1950, when two papers were presented back-to-back, which just tells you how competitive stainless steel and gold had become.²¹ One was presented by Dr Brusse, who spoke about “The Management of Stainless Steel” using modern colored moving pictures; the other was presented by Drs Crozat and Gore, who talked about “Precious Metal Removable Appliances.” The presentations may have instilled some of the same premonitions that man-ape experienced when he encountered early ape-man during that last, fateful day on the savannah of Africa. . . .

Stainless steel is now gaining prominence as the soft brass ligature wire, which was credited to Angle, is now displaced by an 0.254 mm (0.010-inch) soft stainless steel

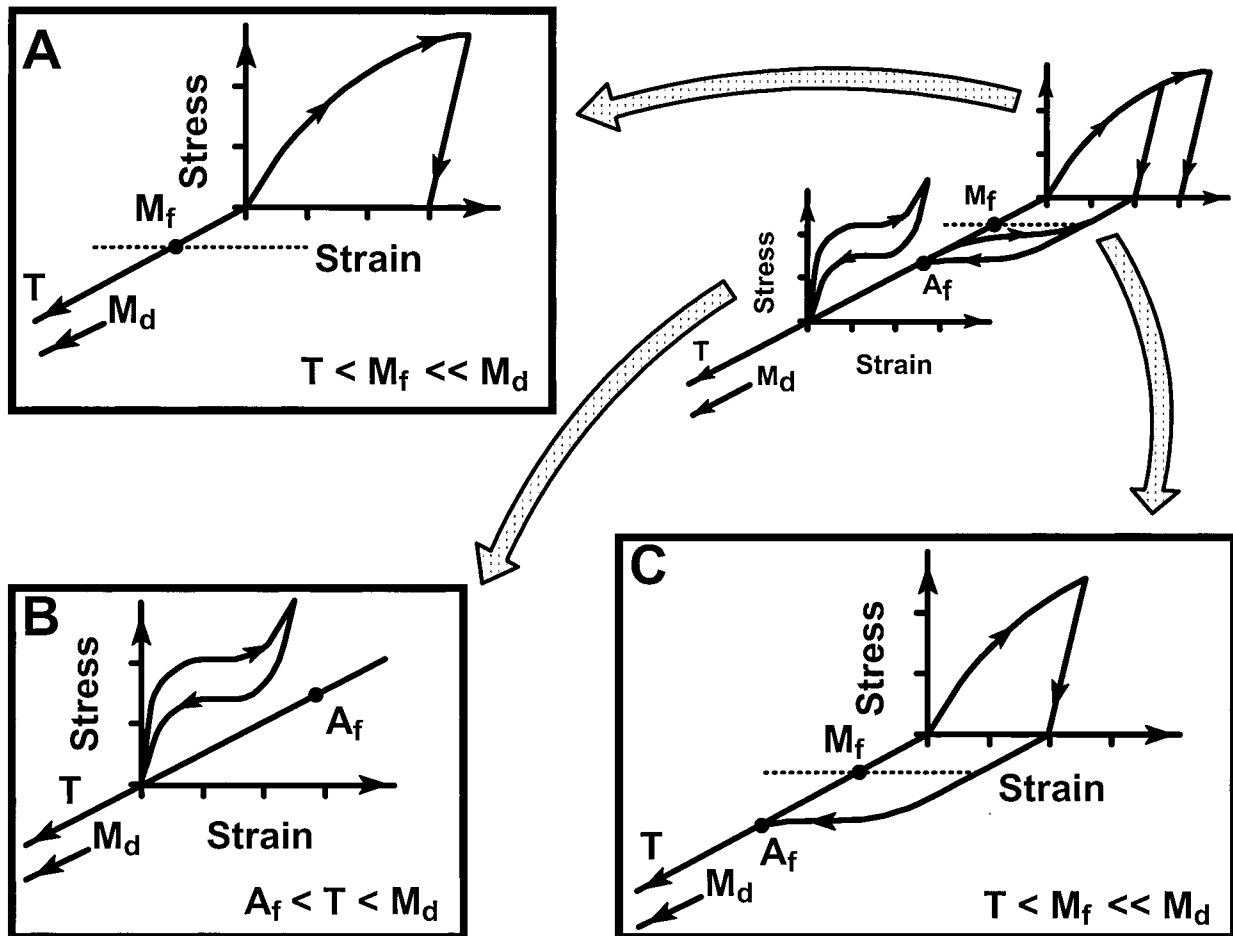


FIGURE 5. Mechanical characteristics of nickel-titanium intermetallic compounds. (A) For a stabilized martensitic material when the temperature is less than the martensite finish temperature (M_f) but the strain (deformation) is more than ca 0.08;^{60,106} (B) for an active austenitic material, ie, a stress-induced martensitic material (SIM), when the temperature is less than the deformation temperature of yielding (M_d) but greater than the austenite finish (A_f) temperature;^{106,107} and (C) for an active martensitic material when the temperature is less than M_f and the strain is less than ca 0.08.^{107,108}

wire.^{18,20} Only 3 years later, Steiner introduces the 0.457 mm \times 0.711 mm (0.018-inch \times 0.028-inch) slot for stainless steel wires in lieu of the 0.559 mm \times 0.711 mm (0.022-inch \times 0.028-inch) slot for gold alloy wires,⁸⁸ and Jackson proposes to eliminate even the Crozat appliance by fabricating it in stainless steel and a nickel-chromium alloy (Tophet metal).²¹ Despite the success of the new slot, the gold Crozat appliance survives to today.⁸⁹ In this period the ligatureless Johnson friction cap appears with its twin-wire configuration, which had existed since the early 1930s (Figure 3A).^{21,90}

To close out this age, a glimmer of things to come is seen as Buonocore⁹⁴ proposes the use of a 30-second, 85% phosphoric acid etch to enhance bonding of acrylic materials to enamel surfaces. This treatment, along with the additions of silane coupling agents to the filler particles⁹⁵ and the use of photoinitiators for the catalyst system,⁹⁶ becomes the basis for the bonding adhesives that would be used to mount brackets directly onto teeth.^{97,98} It is now 1958, and

Dewel unifies the practice and science under one aegis—orthodontics.²¹

PROLIFERATION ABOUNDS

By the 1960s, gold was universally abandoned in favor of stainless steel (Figure 4A).^{65,99} This is how stainless steel was marketed in lieu of gold: (1) the force per unit activation of stainless steel was greater than that of gold (ie, high stiffness was an advantage they claimed); and (2) by being smaller in size, stainless steel appliances were regarded as being more esthetic than gold appliances (ie, the smaller the appliance is, the more it appears to disappear). Stainless steel also had excellent corrosion resistance, work-hardening capabilities, and a frictional magnitude that was so low that it became the standard of the profession.^{100–102} In the 1960s, bracket bands are disappearing as the bonded miniature bracket appears—thereby punctuating the beginning of esthetic orthodontics (Figure 4B). Once again,

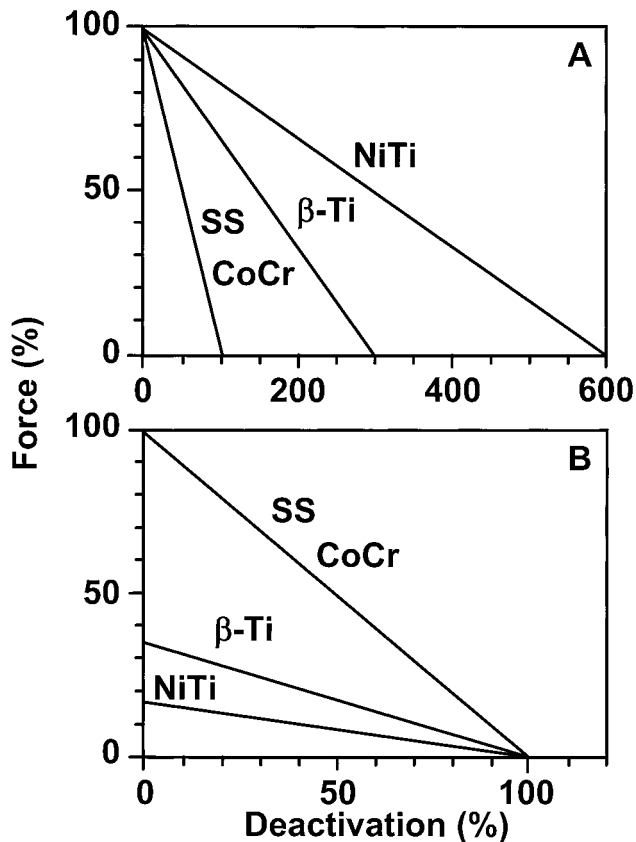


FIGURE 6. Relative force-deactivation characteristics for the four major groups of wire materials—stainless steel (SS), cobalt-chromium (CoCr), nickel-titanium (NiTi), and beta-titanium (β -Ti)—having identical dimensions. (A) When the relative force is maintained constant; (B) when the relative deactivation is maintained constant.

the philosophy was advanced that an appliance, which cannot be made transparent or tooth-colored, should at least be made smaller.¹⁸

In the 1960s cobalt-chromium alloys are introduced (Figure 2B).⁵⁰ These wrought alloys are different from the cast alloys used in prosthodontic dentistry because they contain not only cobalt, chromium, and molybdenum but also substantial amounts of nickel and iron.²⁸ Like stainless steels, they have a high stiffness; but unlike stainless steels, they are available in four different tempers and are heat treatable.^{49,99} Different tempers permit variable amounts of formability, which is required to place loops, V-bends, and various offsets into the archwire. Once deformation is complete, however, heat treatment increases the resilience of the wire by a recommended precipitation- or age-hardening process at 482°C (900°F) for 7–12 minutes.⁴⁹ Unfortunately, most practitioners never exploited this alloy to its full potential. In 1965 the proliferation of materials receives its recognition as the first AAO Committee convenes to discuss specification norms; such meetings continue.

In about 1970, plastic brackets were injection molded from an aromatic polymer, polycarbonate (Figure 4B). Shortly thereafter, practitioners noticed physical and me-

chanical changes associated with stains or odors and time-dependent deformation or creep,¹⁰³ respectively.

In 1962 Buehler discovers nitinol at the Naval Ordnance Laboratory, so-called because it was an acronym for Nickel-Titanium Naval Ordnance Laboratory (Figure 2C).^{33,76,77,104} By 1970 Andreason brings this intermetallic composition of 50% nickel and 50% titanium to orthodontics through the University of Iowa.^{99,105} The Unitek Corporation licenses the patent (1974) and offers a stabilized martensitic alloy that does not exhibit any shape-memory effect (SME) under the name, Nitinol[®] (Figure 5A).^{60,106} This product has the lowest modulus for any cross section and has the most extensive deactivation (range) capabilities.^{54–56} Now light forces can be offered over a protracted range as any of four combinations of passive or active behavior and of martensitic or austenitic phase are possible. In some cases the thermoelastic or the pseudoelastic effects (or both) are also exploited,^{106,108} the latter of which is also termed superelastic, in part because the material has so much springback after displaying what appears to be pure plasticity. By 1986, two “superelastic” alloys are offered—a Japanese NiTi^{109,110} and a Chinese NiTi.^{34,111} These are active austenitic alloys that form stress-induced martensite (Figure 5B).^{106,107} In the early 1990s Neo Sentalloy is introduced as a true active martensitic alloy that undergoes an SME by taking advantage of the pseudoelastic effect during forming and the thermoelastic effect during recovery (Figure 5C).^{107,108} In 1994, three Copper NiTi products are introduced,³⁴ which have chromium in them as well (Table 1),¹¹² and display the SME at 27°C, 35°C, or 40°C. Most recently, nickel-free, titanium-niobium wires have been introduced as a finishing wire.^{36,37,48}

Returning to other materials of the 1970s, elastics of all sorts find their niches in the orthodontic profession. Gum elastics were first employed by Maynard (1843); Tucker (1850) was the first to cut rubber bands from rubber tubing.¹² Independent of whether elastomers are made from ester- or ether-based polyurethanes,²⁹ they possess real limitations with respect to force retention, color fastness, and odor prevention. Plastic coatings on archwires occur too (Figure 4B). One such coating, poly(tetrafluoroethylene) or Teflon[®], has the lowest friction.¹¹³ When this quite soft material is placed in the hostile mechanicochemical environment of the oral cavity, the coating skins off or disappears in as little as 3 weeks.

Self-ligating or ligatureless brackets reappeared in the mid-1970s as Strite, Ltd, marketed them; these brackets had a stainless steel body and a positive-locking, spring-clip mechanism (Figure 3B).^{91,114,115} Their advantage was that unlike conventional ligation, friction is purportedly reduced—but most importantly, friction becomes more reproducible.

In 1977 the beta phase of titanium was stabilized at room temperature, and the aerospace titanium-molybdenum alloy (β -III) was produced (Figure 2D).^{78,99} This beta-titanium al-

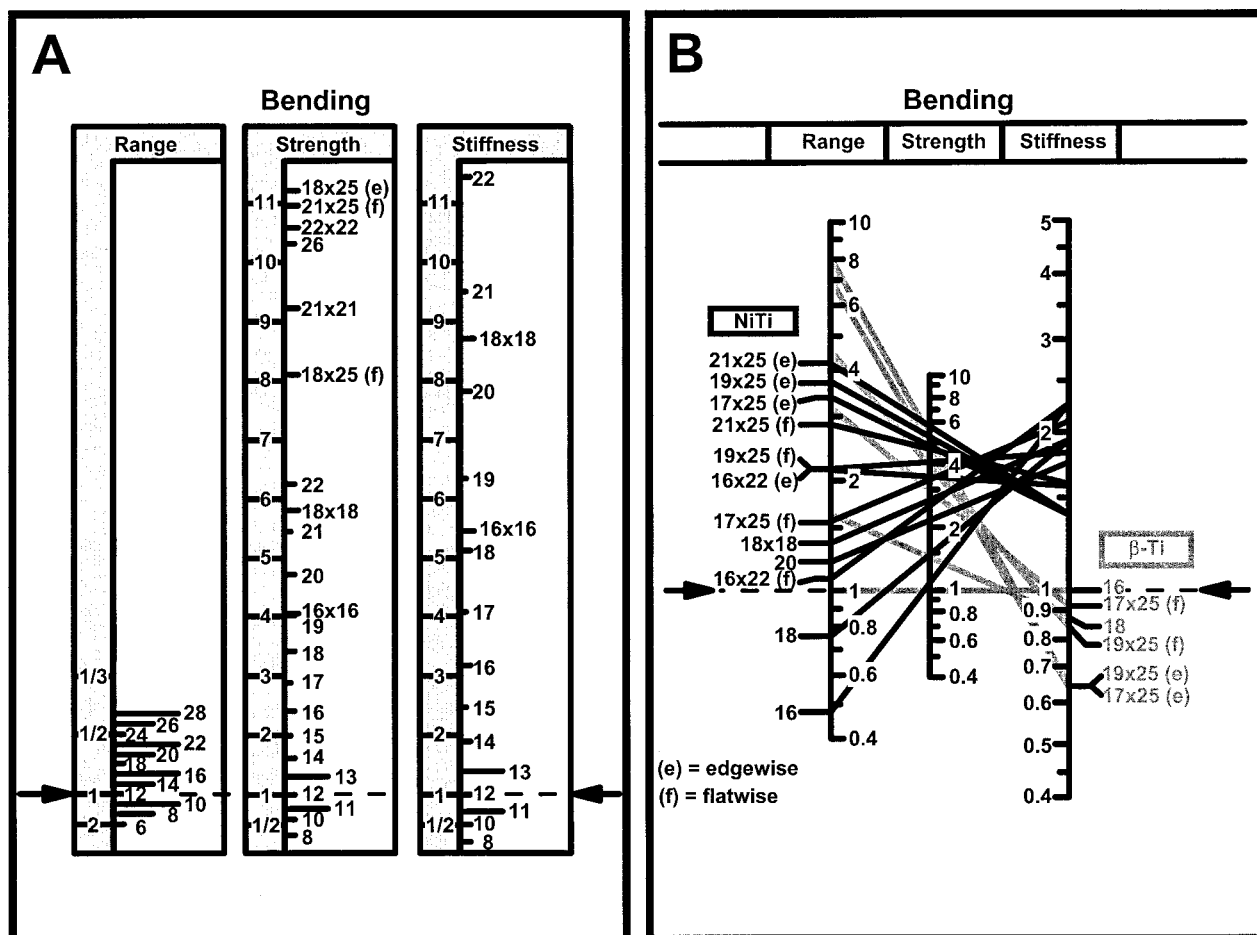


FIGURE 7. Methods to compare elastic property ratios. (A) Tables such as this one to evaluate variable cross-section orthodontics vs a 12 mil (ie, 0.012 inch = 0.305 mm) stainless steel or cobalt-chromium archwire;⁶⁵ (B) nomograms such as this one to evaluate variable cross section and variable-modulus orthodontics vs a 16 mil (ie, 0.016 inch = 0.406 mm) beta-titanium archwire. In general, to convert mil to mm, multiply by 0.0254.¹¹⁷

loy has a modulus closest to that of traditional gold along with good springback, formability, and weldability.²⁴ By the end of the 1970s, four major groups of wire materials came into existence, three of which developed different amounts of range for a given constant force (Figure 6A), or if you kept the same range, they developed different magnitudes of force for a given constant deactivation (Figure 6B). As a consequence, the armamentarium has expanded from just gold or stainless steel, and two slots have been popularized—the 0.559 mm (0.022-inch) slot, which was originally used for gold, and the 0.457 mm (0.018-inch) slot, which was advocated for stainless steel. Within the capabilities of the present armamentarium, both slots become viable alternatives.

At this point, scientific investigators had to decide how to compare the plethora of materials. In the 1940s the strength and flexibility of wrought gold alloys were evaluated using tables that were based on measurements of the proportional limits and the wire diameters.¹¹⁶ Even in Thuro's day, variable cross-section orthodontics was the norm

because stainless steel and cobalt-chromium wires essentially had the same stiffnesses (Figure 7A).⁶⁵ Once the titanium alloys entered the scene, however, variable-modulus orthodontics became possible,¹¹⁸ and elastic property ratios could be derived in which both geometric and material characteristics were important. Using equations, tables, or mathematically based figures called nomograms (Figure 7B),^{46,117,119,120} the practitioner could now compare one wire with another in terms of its three elastic properties of clinical importance: stiffness, strength, and range.

CONSOLIDATION OCCURS

In the 1980s we have esthetic brackets made from single-crystal sapphire (Figure 3C)^{92,121,122} and from polycrystalline alumina (Figure 3D)^{93,123,124}—both having the same inert chemical composition, Al₂O₃. We also have brackets made from polycrystalline zirconia material, ZrO₂,¹²⁵ which reportedly has the greatest toughness among all ceramics.¹⁹ Unfortunately, both these materials inhibit sliding mechan-

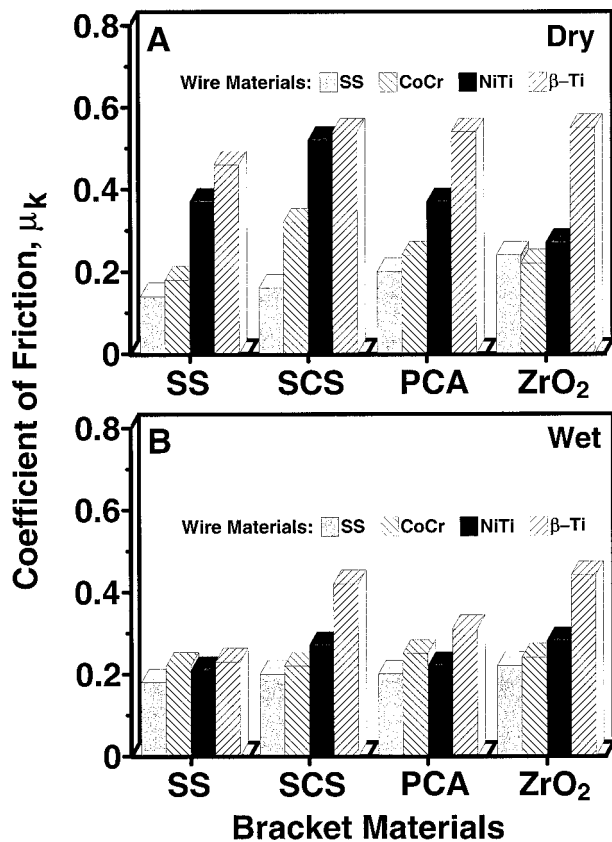


FIGURE 8. Frictional characteristics of various bracket materials (stainless steel [SS],¹³⁶ single-crystal sapphire [SCS],¹²⁴ polycrystalline alumina [PCA],^{123,124,136} and polycrystalline zirconia [ZrO₂]¹²⁵) in combination with metallic archwires (stainless steel [SS], cobalt-chromium [CoCr], nickel-titanium [NiTi], and beta-titanium [β-Ti]) (A) in the dry state; (B) in the wet state using human saliva.

ics,^{125–127} and they have debonding problems.^{123,128} The single-crystal brackets also exhibit specular highlights, whereas some polycrystalline ZrO₂ have intrinsically odd colors. In the early 1990s the first pseudocomposite wire from optical fibers is marketed,^{129,130} which financially is a failure.

From these examples, we can see that this was clearly a period of consolidation, as practitioners were balking from products that just did not work very well (as was the case in the 1970s for the early Nitinol wires), and manufacturers were being compelled either to improve them or remove them from their inventories. Such was the case for early single-crystal sapphire brackets because during torquing, the tie-wings tended to break off or,^{128,131} worse yet, removed facial enamel from the teeth.^{132,133} Moreover, when placed on mandibular incisors or canines, for example, ceramic brackets abraded or chipped the opposing maxillary teeth.^{128,134,135} As if this was not enough, ceramic brackets in combination with any archwire, except nickel-titanium, always produced the highest frictional forces, whether in the dry (Figure 8A) or in the wet (Figure 8B) state.^{124,125,136} Furthermore, optical fibers, whether coated with nylon or hot-melt adhesives, had such low stiffness properties that

they qualified as a “placebo” wire that would only acclimate a patient to the general architecture of his or her appliances.^{129,130} Such a poor performer would later handicap fiber-reinforced composites in the corporate mind of orthodontic manufacturers.

THE COMING OF A NEW AGE

As we enter the 1990s we look back on that century in terms of various type of overall innovations. We had the auto, aviation, polymer, nuclear, space, and computer ages. Indeed, it has been said that more knowledge was amassed in the 20th century than in all previous centuries of mankind. And what we learn about orthodontic materials comes from many of those burgeoning fields. From the viewpoint of true esthetics—in other words, from the viewpoint of not making things smaller but of making them tooth-colored—practitioners assert that esthetics are desirable but that function is paramount. And so as we close this century we begin to see attempts to market a continuous fiber composite, success to manufacture CP-titanium and its products (Figure 4C) (F. Sernetz, personal communication), and modifications to improve sliding mechanics through ceramic-bracket inserts and self-ligating brackets. These topics will be the focus of the next article in the series entitled “Orthodontic Biomaterials: From the Present to the Immediate Future.”

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