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Nitinol Spinal Vertebrae: A Favorable New Substitute

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ABSTRACT

Scoliosis, kyphosis, and bone fracture are health problems, especially of the elderly throughout the world. The vertebra protects the spinal cord. Any impairment to the vertebra can lead to pain and nervousness. Ni-Ti alloy (Nitinol) helps to resolve the problem by fulfilling such requirements as for strength, durability, resistance to wear, and shockwave damping which is due to the shape memory effect. Nitinol medical applications have so far been restricted to surgical devices and orthopaedics. Little has been said about Nitinol use for medication of the spinal vertebra disorder. This article appraises the potential features of Nitinol for vertebral implantation and therapeutic prescription consistent with the specific anatomical variation. Staples, screws, cages, stents, and posterior-stabilizers made of Nitinol have passed in-vitro tests and in some cases in-vivo examinations. Using anatomically tailored Nitinol for treatment and administration of the damaged vertebra is proposed as a forecastable dream.

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1. INTRODUCTION

Back-pain is an annoying problem for people of all ages. However, it is more severe to the elders. The disability-adjusted life years (DALYs) due to low back pain and neck pain have an increased rate of 59% from 1990 to 2015 [1]. As a skeletal muscle disease, almost 80% of people at the age of 50 are experiencing back pain in the US [2] and higher in other parts of the world. In most cases, the cause is vertebral compression fracture [3, 4] due to trauma, osteoporosis, osteoradionecrosis [5], accident, spinal metastasis, excessive pressure, and odd habits.

Treating the back-pain is distressing and expensive [5] because the backbone column is a complicated system having vertebras and cartilages which protect the spinal cord. When noninvasive methods have not been successful, the surgery is recommended [6, 7]. Disc replacement, spinal fusion [8, 9] and vertebral implantation are increasingly implemented year by year. As an example, the number of spinal surgeries in a Japanese multicenter increased from 2004 to 2015 (Figure 1) and is forecasted to almost double until 2019 [10].

During the past five decades, metallic orthopaedic devices have been used for spinal shape correction in scoliosis disease [7, 11–14]. Despite good strength, Young's moduli of metals are higher than bone. High Young modulus leads to stress-shielding which is unfavorable. Young's modulus of a natural bone is around 0.5 to 20 GPa, while that of Nitinol is 30-50, stainless steel 200 and Co-Cr-Mo 240 GPa. Meanwhile, porosity can help to reduce Young's modulus of the metallic parts. Porosity has other benefits like great cell exchange and bone growth [15–19].

Besides mechanical advantages, topographical readiness is also a significant benefit of a metallic implant

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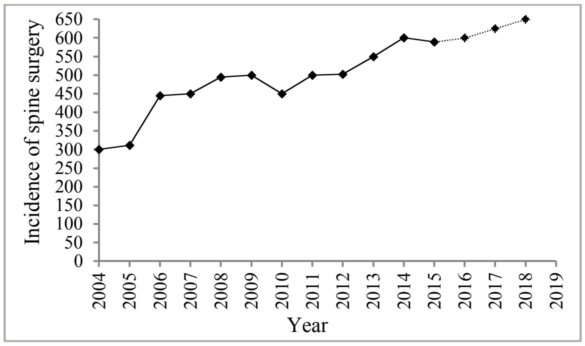

Figure 1. Trend of spine surgeries in a Japanese multicenter (*n*/million general population/year) reproduced with extension from Kobayashi et al. [10]

[15, 20, 21]. Surface-modified porous Nitinol has shown osseointegration, osteoconductivity and appropriate bioactivity [22]. No detectable infection has been observed in both Nitinol in-vitro and in-vivo examinations [23, 24]. The present paper explores possible usage of the porous Nitinol for backbone column implantation. Methods of production, treatment, coating and utilization of Nitinol are summarized with prediction of future vertebral implantation and healing medication.

2. NITINOL

Equiatomic Ni-Ti alloy called Nitinol combines strength, softness, pseudo-elasticity and biocompatibility [7, 25]. With less than 49.4 atom% Ti, the alloy becomes hard and brittle due to the Ni_3Ti intermetallic phase. NiTi monophase is, however, both flexible and rigid depending on the temperature. Superelasticity, biocompatibility, shock damping, fatigue restraint, restricted erosion, biofunctionality, wear opposition, corrosion resistance, shape memory, and stiffness similarity to the bone are some extraordinary behaviors of the Ni-Ti alloy [9, 18, 24–35]. That these characteristics make it superior to other alloys qualifies Nitinol usage for making orthopaedic implants, especially for high loading/reloading regions.

For spinal correction, stainless steel has traditionally been in use for several decades. In recent years, Nitinol has come up with extraordinary attraction stemming from its outstanding features [25, 27]. Lukina, et al. have compared Nitinol with Co-Cr and titanium alloys. According to them, Nitinol resists wear, 100 times better than Ti [36]. Superiority of Nitinol to stainless steel and Ti-Al-V for endochondral bone substitution has be explained by other authors [25]. Tarnita et al. have shown Nitinol resemblance to the bone [37] by indicating self-locking, self-expanding, and self-compression attests [20, 23, 38–40]. Another preference of Nitinol to stainless steel is insensitiveness to the magnetic resonance [41, 42] which eliminates the debris movement concern during the spinal imaging examination. The novelty of the article is reviewing novel and applicable papers in various applications of Nitinol in vertebral region and in order to meet the needs of vertebral implant, Nitinol properties were reviewed to make Nitinol more widely available in implants.

2. 1. Superelasticity (SE) and Shape Memory Effect (SME)

Ni-Ti having 49.0 to 50.7 % Ti can be uniphase and show shape memory effect (Figure 2). The unique SME/SE features of NiTi attributes to the thermomechanical austenite/martensite phase transformation [29, 43–47]. SME is produced by temperature change, while superelasticity appears at loading/unloading treatment [48, 49]. SE is the propensity to return to the previous shape by unloading after the forced deformation. Shape memory is retrieval to the original shape by heating above austenite start transformation temperature [15]. This behavior means remembrance of the austenitic shape as a result of the heat effect [27]. Any exertion of force above A_f and below Md temperature results in the austenite/ martensite transformation [50, 51] which can withstand a strain change of up to 8%. Martensite return to the previous austenitic shape occurs by unloading the loaded sample [43, 52].

Above the austenite finish transformation temperature, NiTi has CsCl-like structure called B2. Below that temperature, the alloy can withhold rhombohedral, tetragonal, orthorhombic or monoclinic structures [48, 53–55]. Repeated conversions can cause "two-way" memory behaviour [50]. Ni-rich Nitinol can exhibit a delicate shape memory behavior related to the B2/rhombohedral structural alteration [16].

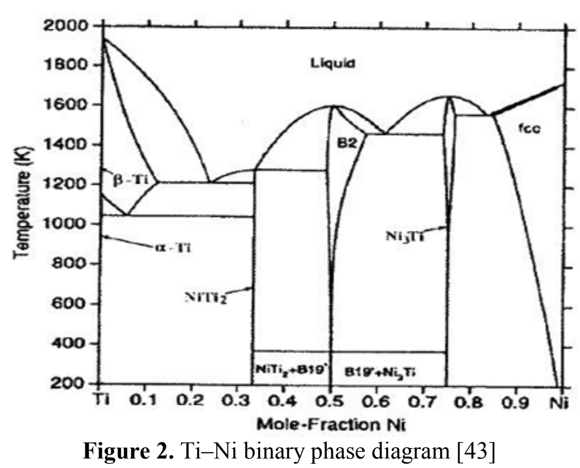

Figure 2. Ti–Ni binary phase diagram [43]

2. 2. Bio Compatibility and Corrosion Resistance Previous studies showed healthy performance of the Nitinol in the limb tissue of the male rat. The alloy biocompatibility, corrosion resistance and non-triggering of the immune system was explained within the acceptable range [56]. Nitinol resistance to corrosion has been better than Co-Cr-Mo and the 316 L. Tahal et al. [25] have observed no particles detached from the implanted Nitinol in the spinal cord. They detected no problem in the Nitinol dura mater implantation and concluded possibility of its safe-use in the intervertebral area. In another study, porous Nitinol showed great osseointegration and biocompatibility, three, six and twelve months after grafting as an interbody fusion implant in a sheep [57, 58].

Despite the above successes, there is a slim chance of Ni release, which may lead to allergic or toxic reactions with the living substances. Surface modification is advisable for enhancement of biocompatibility and bioactivity in some cases. Surface oxidation reduces the chance of corrosion and assures long-term survival [59]. Shot-peening is another example which creates a compression stressed layer with nano-size structure [60].

3. MANUFACTURING TECHNIQUES OF POROUS NITINOL ALLOY

Precise composition control has a crucial role in the structural characteristics of the Nitinol [61, 62]. Method of production influences homogeneity and chemical composition of the alloy, drastically [26]. Any impurity can affect both transformation temperatures and the movement-locking precipitates which substantially deteriorate the alloy performance [53]. Temperature rise alters functional features of Nitinol [29]. Favorable behaviors of the alloy depend on the exact composition of the mono-phase, as illustrated in Figure 2 [62, 63]. Fabrication method and thermomechanical treatments influence on these features [53–55, 63, 64]. SME is monitored by calibration of the pseudo parameters like start/finish transformation temperatures [9].

Because of the high tendency of Ti to react with oxygen, nitrogen, and carbon, Nitinol production milieu must be ultraclean. Ti-Ni tendency to form undesirable brittle phases (i.e. Ni_3Ti and $NiTi_2$) requires well-mixing of the alloy components while reducing the contact time with the holder as short as possible [54, 55, 65]. Microstructural precipitates, inclusions, and grain boundaries form a hierarchical microstructure with variable nanometer to millimeter sizes which affect Nitinol properties [48]. A disadvantage of Nitinol is poor workability which causes heat generation during machining. Intermetallic precipitates decrease workability further due to grain boundary movement prohibition.

The following titles list some common manufacturing techniques usually used for production of nonporous and porous Nitinol:

- Vacuum Induction Melting [29]
- Vacuum Arc Melting [29]
- 3D Printing [66]
- PM: Powder Metallurgy [15, 17, 67]
- HIP: Hot Isostatic Pressure [17, 24, 68]
- SPS: Spark Plasma Sintering [17, 24, 68]
- CS: Combustion Synthesis [15, 54, 69]
- Injection Molding [68]

AM: Additive Manufacturing [44] which includes selective heat sintering (SHS), and sintering at high temperature [15, 54], selective laser melting (SLM) [29, 44, 67], selective laser sintering (SLS) [9], and electron beam melting (EBM) [15].

Each method has its own benefits and deficiencies. Vacuum induction melting and vacuum arc melting are two traditional methods which lead to high contaminants which feature workability reduction [29]. Combustion synthesis (CS) is a subcategory of the thermal explosion process that needs preheating. There are some critical parameters such as process duration, ignition, combustion, and the maximum achievable temperature. Because of the sudden rise of the temperature, the unwanted phases like Ni_3Ti and $NiTi_2$ would not form in this process. These phases do not have any desirable influence on the shape memory effect. Therefore, by sudden heating of the sample, the chance of the unwanted phase formation decreases and the memory properties improves [54]. Nanoparticles achieved by a combination of CS and mechanical alloying (MA) are highly crystalline. The specific surface increase results in osteogenic property improvement [70].

Powder metallurgy and conventional sintering are inexpensive and simple ways which require fine ingredients. Their drawbacks are lengthy procedure, brittle compounds formation, and inhomogeneous distribution of pore sizes [15, 24, 67]. The effect of mechanical alloying and sintering on Nitinol powders have been studied by Sadrnezhaad et al. [71]. They showed that both transition temperatures and apparent porosity depend on the sintering-time, as shown in Figures 3 and 4.

Additive manufacturing is another route to produce complex objects. This technique resolves poor machining problem of Nitinol. Using 3D printer and laser helps fabrication of bars, rods, tubes, sheets and medical devices [44]. It is suitable for production of the complex parts like lattice, truss and hollow objects. Predesigned porous intermetallic-less articles are easy to make by the additive manufacturing.

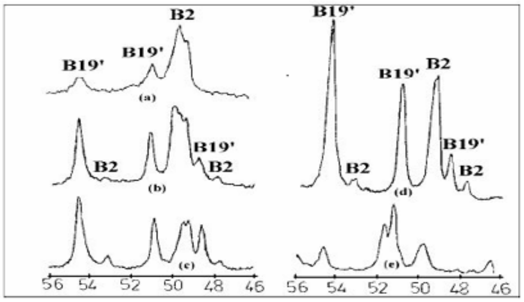

Figure 3. XRD patterns of the sintered Ni-Ti powders milled in argon for (a) 12, (b) 14, (c) 16, (d) 18, and (e) 20 h [70]

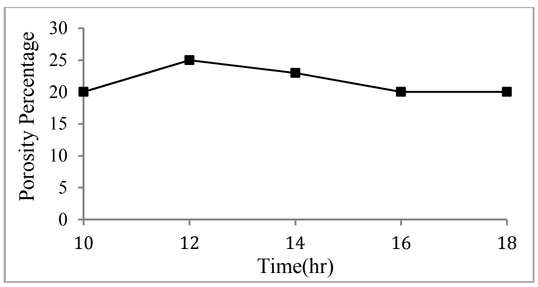

Figure 4. Porosity of the sintered sample against the milling time [70]

Using selective laser melting (SLM) can end-up with rectangular crystals embedding intermetallic phases in the grain-boundaries. Each powder layer melts by laser according to CAD to obtain a 3D part. This method is suitable for fabrication of high purity medical devices [29]. Recent studies working on 4D printing by applying this technique, and the power of the laser affects microstructure and corrosion behavior of the alloy [67]. There are some physical phenomena in the SLM such as thermal stress enhancement and large heating rate. The increase in the transformation temperature relates to the Ni evaporation which reduces nickel content [44].

EBM is similar to the SLM, but the difference is in use of electron beam instead of the laser [66]. For sintering at high temperature (SHS), the powder of Nitinol (or Ni and Ti) are pre-alloyed with a spacer at a moderate temperature. Because of high activity of Ti, the porous product should be sintered under vacuum [15].

SLS is an additive manufacturing method which uses the laser to sinter the powders for forming the desired 3D devices [9]. An interesting manufacturing procedure that attracts lots of attention to surgical planning and implant development is 3D printing that reduces the difficulty of spinal surgeries [72]. Many reports are related to the design of the surgical implants for the spinal region. Using 3D printing eases the surgery, shortens the process, reduces the costs [66], increases homogeneity due to local fusion [72], and improves tissue reconstruction [73].

3D printing is capable of producing anatomically tailored implants. This rapidly growing method is expected to revolutionize the medical implant and device manufacturing in the future. It is capable of making articles in exact compatibility with the patient's anatomy, haematology and pathology [72]. Recent studies on anatomical models, tissue specifications, surgical implants and prostheses fabrication by 3D manufacturing have specified promising results [72–75]. By using neuroimaging, patients anatomy information and software processing, an appropriate implant can be obtained [7], [72]. Work on producing wrist prostheses by 3D printing has gained satisfactory results [21]. For the spine area, high-resolution images of MRI and CT scan can give the data files necessary for exact implant shape [73].

4. APPLICATION OF NITINOL IN THE VERTEBRAL REGION

Drawbacks of the traditional treatments in the vertebral augmentation have forced the specialists to use alternative techniques:

1. Use of bone cement for permanent implantation
2. Application of an osteoinductive and osteoconductive bone cement such as CaP instead of PMMA
3. Use of a metallic vertebral reduction device with a specific shape as an implant [27]. Nitinol is one of the best choices as an implant in spinal surgeries after being tested in neck, lumbar and spine regions in the degenerative and dystrophic diseases (DDD) surgery [74].

Nitinol prostheses used in treatment of the vertebral compression fractures showed immediate and long-term pain relief and restoration of the height of the vertebra. This technique proved safe and effective with significant quality of life improvements [4].

Nitinol has also been used for spinal fusion. As is known, fusion surgery is an acceptable treatment for spinal stenosis, degenerative spondylolisthesis, and disc degradation. Fusion surgery is to connect two or more vertebras in the spine between the two bones permanently, and to prevent remarkably the pain [76]. For this purpose, rigid fixations which have some problems such as retrogression of adjacent parts, inappropriate mechanical properties and stiffness have been used. So the idea of soft fixation or dynamic stabilizers has come up [77, 78]. The superelasticity property of Nitinol could have led to finding the solution [29].

Using Nitinol as an interbody fusion implant relates to its good osseointegration [23, 24, 57]. For spinal treatment, selecting a material with appropriate properties such as bio-functionality and biocompatibility is significant. This has encouraged the researchers choosing Nitinol as a privileged substance of proper biosafety after many chromosol observations and sensitization tests [21].

5. TYPES OF NITINOL VERTEBRAL IMPLANTS

Different shapes of Nitinol can resolve vertebral problems (See Table 1):

5. 1. Rods Idiopathic scoliosis is a 3-dimentional deformation of the spine, vertebral and disc [78]. Nitinol rods with shape memory effect are suitable for scoliosis treatment [11]. The elastic modulus of the alloy should be close to the bone for no stress shielding consequence [25].

Elasticity of the shape memory NiTi has been adequate for surrounding tissue high fusion and low degradation rate [13]. If there is no interaction between implant and the body tissue, implantation rejection may occur. With Nitinol usage, due to good interaction, decrease in the risk of failure has lowered [12].

A comparison of Nitinol with Ti rods applied to 70 patients to improve their degradative lumbar scoliosis showed better spinal deformation correction by the former [7]. Nitinol did not cause spinal canal inflammation and any lymph (and other organs) particle detachment [11]. A single spinal rod of austenitic phase with pedicle screws and a connective bridge has also been presented for scoliosis treatment by Kok et al. [14]. They indicated that at the body temperature, the superelastic rod can easily fit with the anatomical shape of the spine. As the bridges are made of Nitinol, the height of the rod could be adjusted to the surgeon's desired length with a cutter. According to the authors, the system shows higher fatigue resistance in comparison to other Ti alloys, and better torsional yield strength with 30% increase in the torsional stiffness [14].

TABLE 1. The types of Nitinol vertebral implants and their results

Type of nitinol vertebral implant	Application Results
Rods	No inflammation observed in the spinal canal [11] No particle detected in lymph and other organs [11] Suitable for scoliosis treatment [14]
Nails	No adverse reaction detected [79] Suitable for controlling bone modeling [79]
Rings	They can transfer more compression forces to the cage [80] Suitable for neck regions [80]
Staples	Suitable for idiopathic scoliosis treatment, osteotomies and lumbar curve treatments [81, 82]
Cages	Frequent as lumbar interbody in surgeries [9] Better restoring vertebral height than kyphoplasty [27] Self-assembled and being similar to disc [9] Let osteoblasts grow[12]
Screws	suitable for vertebral fusion surgeries [76] Nitinol screws along with Nitinol rods have more flexibility and maintain the spinal movements [76]
Stents	Suitable for vertebral compression fractures treatment [83]
Supporter bands	Used as a posterior tension band in decompression laminectomies [77] Suitable for scoliosis treatments, spine surgery and atlantoaxial instability correction [77] No neurological reaction due to neural compression observed [77]

5. 2. Nails and Rings Implantation of Nitinol nails in rats has shown no adverse effect [79]. Kujala et al. have concluded that the bone modeling is controllable by the Nitinol SMA. Nitinol rings can also serve spinal surgeries in the same way as clamps which are used for quick fixation. This technique requires very small muscle cutting which can reduce bleeding and surgery duration. These rings can transfer some compression forces to the cage. So according to the Wolf's law, the growth rate of the bone increases. Nitinol rings are also presented or neck regions [79].

5. 3. Staples Nitinol staple can be designed straight when at low temperature, but C-shaped when at high temperature for connection of the bone fragments [81]. Complete fusion may be caused by proper biocompatibility, proficient fusion, osseointegration and fixation to the bone for fewer movements [57, 58].

Significant successful results have been obtained by C-shaped NiTi staples used to treat idiopathic scoliosis without fusion [82]. Using a cage in addition to the staples (rather than using the cage alone) in L_4-L_5 vertebras has resulted in excellent achievements. Use of Nitinol staples for osteotomies and lumbar curve treatments has been successful in 86.7% of the cases [81].

5. 4. Cages Cage is a multi-segment device used as a spacer between two vertebras to improve both fusion and bone growth [9]. According to a study, SLS fabricated Nitinol cages have needed finishing by machining and sandblasting. Surgical use of the cages as lumbar interbody has been frequent. One advantage of this method is no nerve compression during the treatment [9].

Using Nitinol for treatment of vertebral compression fractures has resulted in good endplate reduction, biomechanical spinal stability, vertebral heightening and morphology reconditioning [27]. Nitinol has therefore served as an effective biomaterial in restoring vertebral height, even better than kyphoplasty [27]. In 1988 kyphoplasty was suggested as a remedy to lift vertebral endplates aiming at maintaining the height of vertebrae, pain relieving and kyphosis reduction by using bone cement [4]. Decreasing the height of the vertebrae is a critical problem in surgical remedies which is caused by vertical movement of the device [84]. The efficacy of this novel and minimally invasive method is similar to kyphoplasty while there is no need for PMMA and a substitute of dilated balloons [27].

Before insertion, Nitinol cage is flat. Then self-assembles to a disc shape resembling a large oval contacting the cortical bone walls with approachment to the body temperatures [9]. Andani et al. have shown good results of the cage having Nitinol hinges [9]. In some cases, bone grafts have been used in disc space for bioactivity and better fusion. Moreover, the cage has let osteoblasts to grow. However, because of the little contact of the cage with the grafted bone, the results have not been as proper as expected before [12].

5. 5. Screws, Stents and Supporter Bands

The most widely used article in the fusion surgery is the pedicle screw. In vertebral fusion surgery, the two adjacent vertebras are fused by a screw. Nitinol screws along with Nitinol rods have more flexibility in fixation of the spinal movements [74].

Nitinol has a significant effect on development of stent applications [85–91]. Nitinol stents usage in the orthopedic field has been applied to treatment of the vertebral compression fractures having neurological symptoms [83]. Shape memory alloy has also served as a posterior tension band in decompression laminectomies [77]. No neurological reaction due to the neural compression has been observed in this case. These posterior supporters can be used in scoliosis treatments, spine surgery and atlantoaxial instability correction [77].

6. IN-VIVO STUDIES

As Table 2 shows, the in-vivo studies with the NiTi alloy indicates excellent biocompatibility with great suitability for implantation in a living organ.

TABLE 2. The In-vivo studies for the biocompatibility assessment of the NiTi alloys using animal species.

Animal model	Duration of implantation	Control materials	Major results
Rabbits' femur	6 and13 weeks	Uncoated NiTi	After 6 weeks direct Bony coverage of bioactive NiTi was observed, and after 13weeks the interface between the coated implants and the bone shows the nature of osteo-bonding [92].
Rabbit's femur	13 weeks	Ti	Porous NiTi implants offer faster osteointegration and better osteoconductivity than porous Ti implants [93].
Rabbit's femur	13 weeks	Ti	Dense Ti implants show higher Bonding strength than dense NiTi due to the better Biocompatibility [93].
Rabbit's femur	15 weeks	Bulk NiTi	Good bone-implant contact can be obtained for porous NiTi alloy and exhibits better osteoconductivity and osteointegration than bulk One [22].
Pigs' spine	3 months	nothing	No significant release of Ni into the blood was detected 3 month after placement [11].
Femoral shafts of dogs	12 weeks	316L stainless steel	Since the elastic modulus of NiTi is lower, the stress-shielding effect in the bone underneath NiTi device is less than 316L stainless steel [94].
Long crus of the incus and the incus of ears of cats	355 days	nothing	Concluded that the biocompatibility of NiTi alloy stapes prosthesis with the long crus of the incus was proven [95].

7. FUTURE DIRECTION

By reviewing the implants used in the treatment of lumbar disease, recognizing the benefits and the potential of various Nitinol implants for the treatment of these diseases seems necessary to lead researchers and surgeons. Optimization the topology of these implants in order to enhance osteointegration and efficiency of Nitinol properties should be developed and expanded. By using 3D printing method, a suitable morphology for cell adhesion can be designed.

Nitinol is suitable for using in lumbar implants, but there are still restrictions on the use of this alloy due to the toxicity and sensitivity of nickel that can be eliminated by biomaterial strategies. For example, by adding certain amounts of an element in this alloy, while maintaining the properties of Nitinol, the amount of nickel is reduced. In addition to assessing the biocompatibility of these implants in the animal model, consideration of other Nitinol properties is necessary to evaluate the effectiveness of NiTi which should be widely investigated and reported.

Currently, the use of rods for the treatment of scoliosis is greater and the other implants mentioned in the article are less commonly used. Therefore, there is a need for more articles in in-vivo experiments to determine the advantages and disadvantages of these implants.

8. CONCLUSIONS

Suitable properties of Nitinol prove it an exceptional biomaterial for medical implantation especially for orthopedic applications.

By comparing NiTi interbody fusion with Ti alloy cages used in the spinal area, it can be concluded that integration of NiTi is three times better than the latter. Specifically, NiTi has shown 75%, while Ti alloy has demonstrated 25% integration.

Considering the importance of fatigue in the working conditions of the alloys, Nitinol has much more compression fatigue resistance than Ti and Co-Cr-Mo alloys.

Softness and flexibility of Nitinol SMA rods at low temperatures allows their easy implantation, long time surgery and the bleeding vertebrae scoliosis treatments. The surgery duration of scoliosis by SMA implant is 284±5 min with 585±288 ml bleeding, while for traditional alloys, it is 324±4 min with 778±285 ml bleeding [96].

Stapling the NiTi alloy in lumbar curve have resulted in 86.7% success which is considered great. The biocompatibility of NiTi is close to or even better than that of the stainless steel and Ti6Al4V. NiTi shape memory effect and corrosion resistance compares well to the stainless steel and Co-Cr-Mo. NiTi can, therefore, be considered a best choice for vertebra surgical treatment and other orthopedic applications. Since processing and implantation have significant influence on the final NiTi performance, careful consideration of all engineering and medical treatments must be considered.

9. ACKNOWLEDGMENTS

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Nitinol Spinal Vertebrae: A Favorable New Substitute

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چکیده

اسکولیوز، کیفوز، و شکستگی استخوان، از جمله مشکلاتی است که برای سلامتی افراد به ویژه سالمندان در سراسر جهان ایجاد می‌شود. از آنجا که مهره‌ها نیز وظیفه محافظت از نخاع را به عهده دارند، هرگونه آسیب به مهره ممکن است منجر به درد و ناراحتی در بیمار شود. آلیاژ Ni-Ti با دارا بودن خواصی همچون استحکام، دوام، مقاومت در برابر سایش و جاذب شوک بودن که به دلیل اثر حافظه‌داری آن است، برای حل مشکلات ذکر شده کمک‌کننده است. تاکنون کاربردهای پزشکی نایتینول محدود به ابزارهای جراحی و ارتوپدی بوده است و خیلی کم از آن برای درمان ناهنجاری‌های ستون فقرات بهره برده شده است. این مقاله ویژگی‌های بالقوه نایتینول را به عنوان جایگزین مهره و همچنین درمان مطابق با شرایط آناتومیکی را ارزیابی می‌کند. آزمایش‌های in-vitro و در برخی موارد in-vivo بر روی منگنه‌ها، پیچ‌ها، قفس‌ها، استنت‌ها و تثبیت‌کننده‌های خلفی ساخته شده از نایتینول انجام شده است. امید است بتوان از ناتینول آناتومیکی مناسب برای درمان مهره‌های آسیب‌دیده استفاده کرد.

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