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Regional load deflection rate of multiloop edgewise archwire

Byoung-Ho Kim[1], Won-Sik Yang[2]

This study was conducted in order to analyze the mechanical characteristics of multiloop edgewise archwire (MEAW). The purposes were 1) to compare load deflection rate (LDR) of MEAW with that of various other arch wires in the individual interbracket span, 2) to compare the wire stiffness in the interbracket span with that in the multi-L-loop region (the span from distal border of the bracket of the lateral incisor to the mesial border of the buccal tube of the second molar), and 3) to verify the experimental results with theoretically derived formula. The single L-loops of five different horizontal lengths and multi-L-loops for the upper and lower arches were made out of .016×.022 permachrome stainless steel wire. Straight segment of plain stainless steel, TMA and NiTi wire of the same dimension were prepared. The LDR was measured using Instron model 4466 with the load cell of 50N capacity at cross head speed of 1.0mm/min, and maximum deflection of 1.0mm. Five specimens were tested under each experimental condition. The wire stiffness number for each interbracket region and multi-L-loop region was calculated from the LDR and the interbracket spans. By dividing the theoretical model of multi-L-loop into 35 linear segments, the energy stored in each segment was obtained. Then the LDR and wire stiffness of single L-loop and multi-L-loop were calculated and compared. The findings were as follows : 1) The average LDR of MEAW in the individual interbracket region was 1/1.53 of that of the NiTi, 1/2.47 of TMA and 1/5.16 of the plain stainless steel wire. 2) The wire stiffness of MEAW in the multi-L-loop region was 1.53 times larger than that in the interbracket region, and the LDR was almost twice as large as that of NiTi in that region. 3) According to the theoretically derived equation, the wire stiffness of the single L-loop was lower than that of multi-L-loop.

The results of this study suggest that MEAW has the unique mechanical property which could allow individual tooth movement and transmit elastic force effectively through the entire arch wire.

Key Words : Regional, Load deflection rate, Wire stiffness, MEAW, TMA, NiTi

Load deflection rate (LDR) is defined as the force/displacement ratio that is a measurement of resistance to deformation. It is also a measurement of the force required to bend, or otherwise deform material for a specific amount. Orthodontic appliances with high LDR apply excessive force on the tooth, and the force decreases quickly with tooth movement. Appliances with low LDR, on the other hand, can maintain the forces in the desired level and maximize the rate of tooth movement.[1)]

In the multiloop edgewise archwire (MEAW) technic, multiple L-loops are utilized to decrease the LDR in the interbracket span, making it possible to upright posterior teeth, to change the inclination of

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Table 1. The horizontal length of L-loop in each interbracket region used in this study (unit: mm)

Region *(tooth number)*	1~2	2~3	3~4	4~5	5~6	6~7
Maxilla	0.0	6.0	8.0	8.0	8.0	9.0
Mandible	0.0	5.0	7.0	7.0	8.0	9.0

the occlusal planes, and to correct sagittal and vertical relationship of the occlusion in a relatively short time.[2)] Other studies have described these unique properties of the MEAW as resulting from its lower stiffness in comparison to those of a plain stainless steel wire.[3,4)] Because nickel titanium wires possess much lower LDR than the MEAW, Enacar[5)] suggested that the nickel titanium wires with a second order curve could work as MEAW in correcting the openbite. According to Lee and Nahm,[6)] however, when the anterior vertical elastics were applied to nickel titanium wire, the elastic forces were concentrated on canines. They also pointed out that the pattern of action of nitinol was different from that of MEAW. In other words, the fact that MEAW has a low load deflection rate in its entirety cannot explain alone the effectiveness of MEAW. Furthermore, Kim[7)] explained that the L-loop of MEAW served as a break between adjacent teeth, and provided horizontal and vertical individual tooth movement. The breakage in the continuity of the wire means not only that the resistance against the wire deflection between adjacent teeth is low, but also that the wire should have a lower LDR in the interbracket span to allow for individual teeth movement.

Until now, the LDR of MEAW in the interbracket regional level has not been studied. Therefore this study was conducted in order to analyze the mechanical characteristics of the MEAW. The purposes were 1) to compare its LDR with that of various other arch wires at the individual interbracket region, 2) to compare the wire stiffness in the interbracket region with that in the multi-L-loop region (the span from distal border of the bracket of the lateral incisor to mesial border of buccal tube of the second molar) and 3) to verify the experimental results with the theoretically derived formula.

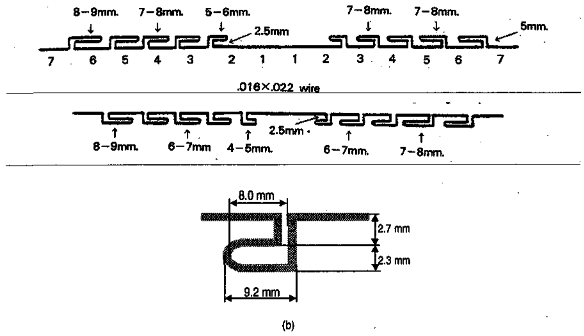


Fig. 1. (a) The diagram of the MEAW (courtesy of Dr. Young H. Kim).
(b) Example of an L-loop with 8mm of loop length

MATERIALS AND METHODS

1. Preparation of the specimens

For the test in the interbracket region, the single L-loops in five different lengths of the horizontal part, and for the test in the multi-L-loop region, the multi-L-loops for the upper and lower arches were made out of .016 × .022 Permachrome stainless steel as described by Kim[7)] (Fig. 1, Table 1). The multi-L-loops were fabricated as they would fit the average sized dentiform. The wires were then treated thermally at 475℃ for 3 minutes[8)] and electrically polished for 5 seconds (Big Jane Model E3762). The segments of stainless steel, TMA, and nickel titanium wires in .016×.022 size were used (Table 2).

2. Measuring the LDR at the level of interbracket span

One end of the wire to be tested was engaged in the bracket that was welded to the stainless steel

Table 2. The materials used in this study

	Manufacturer	Commercial name	Size of cross section(mm)[2]
L-loop[1]	Unitek	Permachrome Standard	0.406×0.556
Stainless steel wire	Unitek	Permachrome Standard	0.406×0.559
β-titanium wire	Ormco	TMA	0.420×0.558
Nickel titanium wire	Ormco	NiTi	0.401×0.542

[1] The specimens were thermally treated and electrically polished.
[2] The size of wires was measured with micrometer (Mitutoyo Co. Scale: 0-25mm).

Table 3. Interbracket spans in each of region used in this study (unit: mm)

Region *(tooth number)*	1~2	2~3	3~4	4~5	5~6	6~7
Maxilla	6.0	5.5	6.0	4.5	6.0	7.0
Mandible	4.0	4.5	6.0	4.5	6.5	9.0

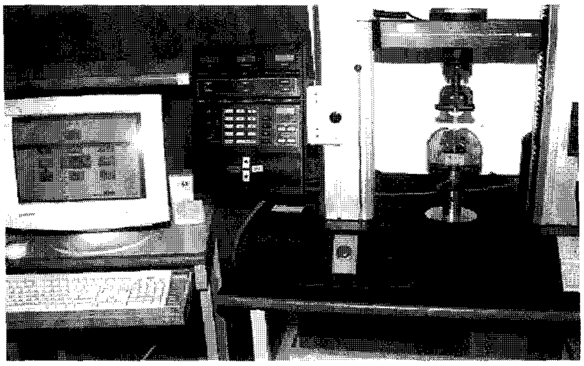


Fig. 2. Instron model 4466 and its computer system including its software, Series IX.

fixture that was fixed by the lower grip. The other end of the wire was fixed in the same manner by the upper grip at various interbracket span as measured by the dentiform manufactured with the average tooth size on which the standard brackets(Tomy Co.) were bonded at the ideal position (Table 3).

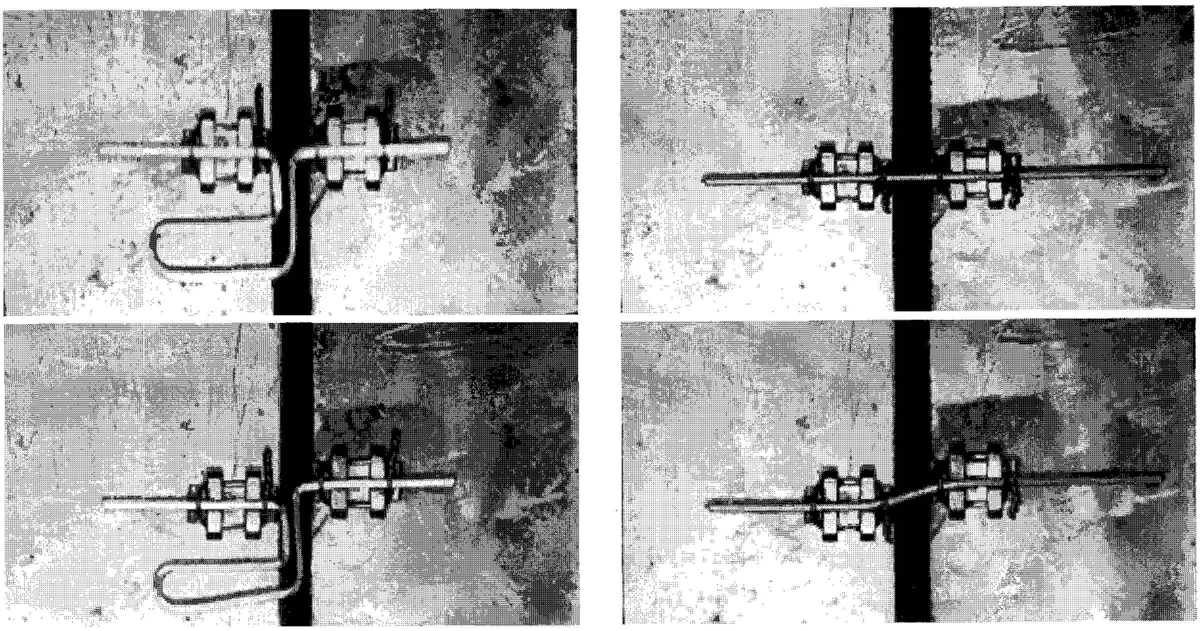
Instron (model 4466) universal testing machine and the software Series IX was used (Fig. 2). The LDR was measured at the cross head speed of 1mm/min, and maximum deflection of 1.0mm. The capacity of load cell was 50N. Five specimens were tested under each experimental condition in order to eliminate the possibility of changes which may occur in the physical properties of wires caused by the stress from repeated measurement (Fig. 3 a, b). In the case of L-loop, it was activated in the direction of closing the loop. The specimen of NiTi and TMA were tested in the thermostatic water bath which was maintained at the temperature of 37℃ (Fig. 3 c, d).

3. Measuring the LDR of the multi-L-loop region

The anterior part of multi-L-loop wire was fixed to the lower fixture with the loops directed downward. The hook fixed to upper fixture was positioned at a distance of 42.0mm from the lower fixture (Fig. 4 a, b). Straight stainless steel wire, TMA and NiTi wires were fixed to the lower fixture with the depth of 5mm or more. And the testing span was also maintained at a distance of 42.0mm (Fig. 4 c, d). The LDR was measured at cross head speed of 1.0mm/min, and maximum deflection of 10mm. 5 specimens were tested for each wire.

4. Data analysis

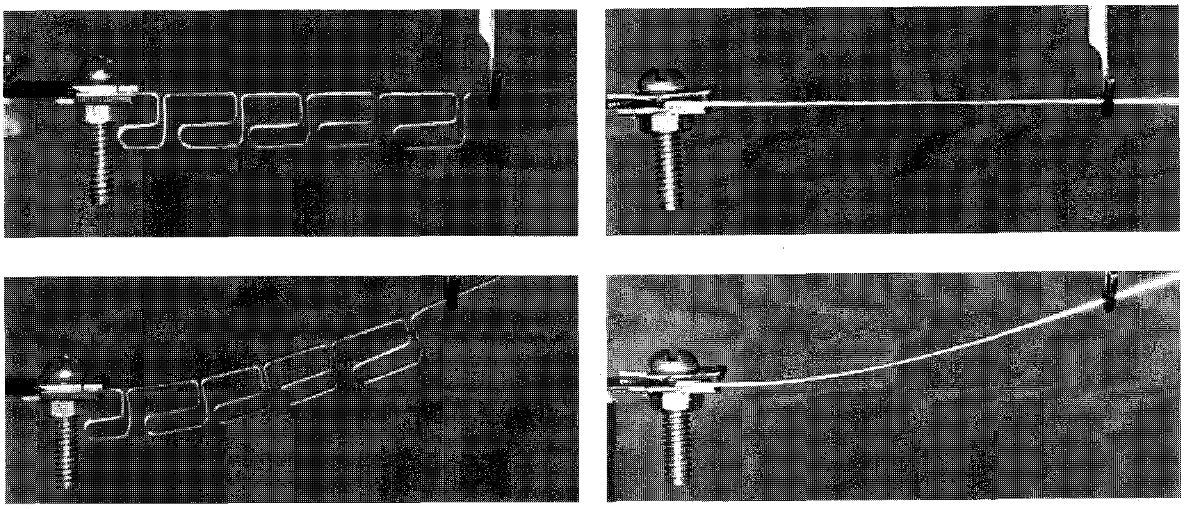
The data (deflection and load) was transmitted from the load cell to the software (Series IX



a) A L-loop : top : in a passive state, bottom : in activation

b) A plain wire : top : in a passive state, bottom : in activation

Fig. 3. Test in the interbracket region.



a) A multi-L-loop

b) A plain wire

Fig. 4. Test in the multi-L-loop region.

automated Material Testing System) in the computer connected to the Instron. The load-deflection curves were plotted and the load deflection rates were given by the slope of the linear portion of the curve. The wire stiffness number under each condition was calculated from the regional LDR and the length of span using Dr. Burstone's method.[10] Coefficient of variation at each tested material was obtained for the examination of the homogeneity of specimens.

Table 4. The LDR of various wires in each maxillary interbracket region (unit: gm/mm, Mean±S.D.)

Region (tooth number)	Span (mm)	L-loop	NiTi	TMA	Plain stainless steel
1~2	6.0	*	340.38±12.87	557.70±17.98	1228.10±19.69
2~3	5.5	406.98 ± 8.23	419.47±21.11	660.15±21.98	1437.85±45.76
3~4	6.0	201.52 ± 4.98	340.38± 7.54	557.70±22.12	1228.10±41.80
4~5	4.5	252.12 ± 8.43	653.14± 9.28	1012.44±20.54	2003.87±91.96
5~6	6.5	188.34 ±11.81	294.82±14.35	497.19±25.15	1074.67± 9.91
6~7	7.0	144.85 ± 1.38	257.31± 2.93	444.34± 6.44	888.16±61.72

* Because the L-loop is not utilized in the region between the central incisor and the lateral incisor, the value of the L-loop is the same as that of a plain stainless steel wire.

Table 5. The LDR of various wires in each mandibular interbracket region (unit: gm/mm, Mean±S.D.)

Region (tooth number)	Span (mm)	L-loop	NiTi	TMA	Plain stainless steel
1~2	4.0	*	810.45±16.34	1305.66±15.87	2486.15±87.55
2~3	4.5	598.00 ±10.85	653.14± 9.28	1012.44±20.54	2003.87±91.96
3~4	6.0	303.02 ±11.55	340.38± 7.54	557.70±22.12	1228.10±41.80
4~5	5.0	354.83 ± 8.46	518.69±11.61	835.63± 5.99	1685.39±15.76
5~6	6.5	188.34 ±11.81	294.82±14.35	497.19±25.15	1074.67± 9.91
6~7	9.0	112.33 ±17.38	156.26± 6.46	227.58±19.96	490.88± 6.42

* Because the L-loop is not utilized in the region between the central incisor and the lateral incisor, the value of the L-loop is the same as that of a plain stainless steel wire.

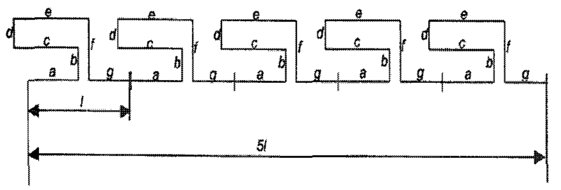


Fig. 5. Segments of multi-L-loop for derivation of the theoretical formula.

5. Derivation of the theoretical equation

Multi-L-loop composed of 5 loops were divided into 35 segments (Fig. 5). Using Timoshenko's energy theorem, the value of the energy stored in each segment by the load was obtained by integration of the square of moment, and the total energy was calculated. Using Castigliano's theorem, the deflection versus load was obtained through the partial differentiation of the energy with respect to the load.[9] Then, the wire stiffness of the single L-loop and the multi-L-loop was calculated theoretically.

RESULTS

1. LDR in the interbracket region

The values of LDR at various interbracket spans were obtained as shown in Table 4 and 5. The results show that the LDR of the L-loops in the interbracket region is 1/1.53 of NiTi, 1/2.47 of TMA, and 1/5.16 of plain stainless steel wire on the average (Table 6).

According to the coefficent of variation of each specimen, the L-loop had the greatest variation, followed by TMA, stainless steel and NiTi (Table 7).

Table 6. The ratio of regional LDR of NiTi, TMA and stainless steel as compared with L-loop

Region(tooth number)	L-loop	NiTi	TMA	Plain stainless steel
Maxilla				
1~2	1.00[1)]	0.28	0.45	1.00
2~3	1.00	1.03	1.62	3.53
3~4	1.00	1.69	2.77	6.09
4~5	1.00	2.59	4.02	7.95
5~6	1.00	1.57	2.64	5.71
6~7	1.00	1.78	3.07	6.13
Mandible				
1~2	1.00[1)]	0.33	0.53	1.00
2~3	1.00	1.09	1.69	3.35
3~4	1.00	1.12	1.84	4.05
4~5	1.00	1.46	2.36	4.75
5~6	1.00	1.57	2.64	5.71
6~7	1.00	1.39	2.03	4.37
Average[2)]	1.00	1.53	2.47	5.16

[1)] Because the L-loop is not utilized in the region between the central incisor and the lateral incisor, the value of the L-loop is the same as that of a plain stainless steel wire.

[2)] Average was calculated excluding the first region, because the L-loop is not utilized in this region.

Table 7. The coefficent of variation(C.V.) of each specimen used in the interbracket region test(%)

Region(tooth number)	L-loop	NiTi	TMA	Plain stainless steel
Maxilla				
1~2	1.60	3.78	3.22	1.60
2~3	2.02	5.03	3.33	3.18
3~4	2.47	2.22	3.97	3.40
4~5	3.80	1.42	2.03	4.59
5~6	6.27	4.87	5.06	0.92
6~7	0.95	1.14	1.45	6.95
Mandible				
1~2	3.52	2.02	1.22	3.52
2~3	1.81	1.42	2.03	4.59
3~4	3.81	2.22	3.97	3.40
4~5	2.38	2..24	0.72	0.94
5~6	6.27	4.87	5.06	0.92
6~7	15.47	4.14	8.77	1.31
Average	4.53	2.95	3.40	2.94

2. LDR in the multi-L-loop region

The results in the multi-L-loop region were different from those in the interbracket region. The multi-L-loop fabricated according to average sized upper dentition had the LDR of 1/3.19 of plain stainless steel of same length. In the case of lower multi-L-loop, the ratio of LDR with plain stainless steel wire was

Table 8. The LDR of upper and lower multi-L-loop region and 42mm span for plain wires

	LDR(gm · f/mm) Mean±S.D.	C.V.(%)	Ratio compared with maxillary multi-L-loop	Ratio compared with mandibular multi-L-loop	Average ratio
Maxillary multi-L-loop	0.577±0.042	7.31	1.00		1.00
Mandibular multi-L-loop	0.618±0.038	6.16		1.00	
NiTi	0.314±0.033	10.46	0.54	0.51	0.53
TMA	0.847±0.023	2.67	1.47	1.37	1.42
Stainless steel wire	1.839±0.055	2.98	3.19	2.97	3.08

Table 9. Wire stiffness number of each region

Region (tooth number)	Span (mm)	L-loop	NiTi	TMA	Plain stainless steel
Maxilla					
1~2	6.0	634.93	175.98	288.33	634.93
2~3	5.5	176.80	182.23	286.78	624.64
3~4	6.0	104.19	175.98	288.33	634.93
4~5	4.5	73.32	189.94	294.43	582.75
5~6	6.5	114.28	178.88	301.67	652.07
6~7	7.0	101.93	181.07	312.68	624.99
Multi-L-loop region or 42mm span	42.0	187.59	102.14	275.22	597.57*
Mandible					
1~2	4.0	571.27	186.22	300.01	571.27
2~3	4.5	173.91	189.94	294.43	582.75
3~4	6.0	156.66	175.98	288.33	634.93
4~5	5.0	127.39	186.22	300.01	605.10
5~6	6.5	114.28	178.88	301.67	652.07
6~7	9.0	130.67	181.77	264.73	571.02
Multi-L-loop region or 42mm span	42.0	200.91	102.14	275.22	597.57*

* The wire stiffness number of 016×022 stainless steel wire is 597.57(Burstone,[10] 1981).

1:2.97. The LDR of multi-L-loop is larger than that of NiTi, and smaller than TMA (Table 8).

3. Wire stiffness number

In the region between the upper first and second premolar, the L-loop had the least wire stiffness. The wire stiffness numbers of L-loop at each interbracket region except the region between central and lateral incisor were smaller than those of upper and lower multi-L-loop. But in the case of NiTi, the wire stiffness numbers of the regional interbracket spans were about 1.78 times as large as that of 42mm span. In general, TMA and plain stainless steel wire had slightly larger wire stiffness number in the interbracket region (Table 9, 10).

Table 10. Ratio of wire stiffness number of each interbracket region as compared with multi-L-loop region

Region (tooth number)	Span (mm)	L-loop	NiTi	TMA	Plain stainless steel
Maxilla					
1~2	6.0	3.38	1.72	1.05	1.06
2~3	5.5	0.94	1.78	1.04	1.05
3~4	6.0	0.56	1.72	1.05	1.06
4~5	4.5	0.39	1.86	1.07	0.98
5~6	6.5	0.61	1.75	1.10	1.09
6~7	7.0	0.54	1.77	1.14	1.05
Mandible					
1~2	4.0	2.84	1.82	1.09	0.96
2~3	4.5	0.87	1.86	1.07	0.98
3~4	6.0	0.78	1.72	1.05	1.06
4~5	5.0	0.63	1.82	1.09	1.01
5~6	6.5	0.57	1.75	1.10	1.09
6~7	9.0	0.65	1.78	0.96	0.96
Average		0.65	1.78	1.07	1.03

4. Derivation of theoretical equation of LDR of multi-L-loop

The LDR of multi-L-loop in corporated with 5 loops was derived as follows :

$$\frac{\delta}{P}=\frac{1}{LDR_{5loops}}$$
$$=\frac{2}{EI}\sum_{n=0}^{4}\left[-\frac{(nl)^3}{6}+\frac{(nl+g)^2f}{2}+\frac{(nl+g+e)^3}{3}+\frac{(nl+g+e)^2d}{2}-\frac{(nl+g+e-c)^3}{3}+\frac{(nl+g+e-c)^2b}{2}+\frac{(n+1)^3l^3}{6}\right]+\frac{5(f+d+b)}{AE}$$

(P : Load, δ : deflection, LDR_{5loops} : LDR of multi-L-loop, E : elastic modulus, I : moment of inertia, A : area of cross section, *a, b, c, d, e, f, g* : length of each segment, l : horizontal length of base of the single loop = $a-c+e+g$, Fig. 5)

Determination of the wire stiffness of the multi-L-loop and single L-loop was the result of multiplying the theoretically derived LDR by the third power of the horizontal length of the multi-L-loop. By inserting the arbitrary length of each segment in the equation, the values of wire stiffness of single L-loop and multi-L- loop were obtained. As shown in table 11, wire stiffness of multi-L-loop incorporated with five L-loops is 1.52 times as large as that of single L-loop.

DISCUSSION

1. Clinical significance of the LDR

There are various ways of describing the physical properties of orthodontic wires. In the case of elasticity or stiffness, there are 3 areas of measurement: material stiffness, wire stiffness and appliance stiffness.[10] First, the material stiffness is defined as the ratio of unit stress to unit strain, usually expressed as psi, pascal, or N/㎟ in accordance with Young's modulus or modulus of elasticity. It describes the inherent elastic properties of the wire material regardless of the length and the cross sectional geometry.

Second, the wire stiffness describes the inherent stiffness of a given wire as determined by the cross-sectional geometry and the material, but not by the length or wire design. It represents flexural

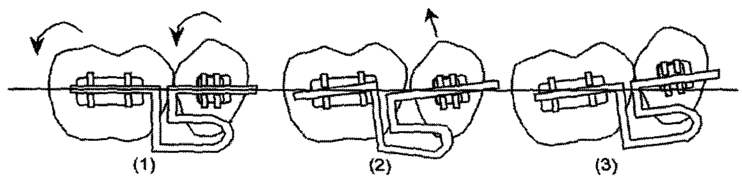


Fig. 6. The situation of uprighting the posterior teeth and changing the inclination of occlusal plane with MEAW mechanics (The diagram is somewhat exaggerated).

(1) Tip back moment which has been constructed in activating the MEAW is acting on the posterior teeth for uprighting. This movement of individual teeth is allowed by breakage of continuity of the wire.

(2) The L-loop is compressed slightly with the tooth movement. Elastic force transmitted from anterior region makes the anterior tooth extrude.

(3) Consequently, the occlusal plane is changed.

rigidity(N㎟, pound · $inch^2$) of a wire and depends on its elastic modulus of the wire and the moment of inertia. The advantage of dealing with flexural rigidity rather than elastic modulus is that it is of immediate clinical relevance. Wires of different shape, size, and construction can be directly compared.[11]

Third, the appliance stiffness, determined by the length and other design factors (such as a loop) of a wire of specified size and material, is represented by LDR which measures the load required for a unit length of deflection. In orthodontics, the LDR is the force generated by an orthodontic appliance causing unit deflection. The LDR of an orthodontic appliances is, therefore, dependent upon the wire material (material stiffness; N/mm^2) represented by Young's modulus, the cross-sectional geometry(cross-sectional stiffness or moment of inertia; mm^4), and design factor of wires (appliance design stiffness; mm^{-3}).[10,12]

LDR = wire stiffness × design stiffness
(wire stiffness = material stiffness × cross-sectional stiffness)

Waters[11] mentioned that wires with low stiffness were not necessarily advantageous in orthodontic treatment in every instance. While NiTi wires of low stiffness were recommended for severely malpositioned teeth in the early stages of treatment, it would be less suitable for stabilizing components such as buccal sections that have to resist forces such as those exerted by intermaxillary elastics. TMA can be deflected approximately twice as much as stainless steel wire without permanent deformation and it delivers force values less than half that of stainless steel, so it is better in the middle stages of the treatment.[13,14]

Waters[11] mentioned that looped arches could offer enough stiffness for the stabilizing sections of the arch and but also offer flexibility where it is required.

2. Considerations on the design of the experiment

In general, there are many methods of testing the elasticity of orthodontic wire materials.

When the orthodontic wire is exposed to the bending force or torsional force, the inner fiber of the wire is compressed, and the outer fiber elongated.[15] Because it is difficult to understand the inherent properties of the material using the bending or torsional test, the tension test along the neutral axis is preferred in quantifying the mechanical properties of the wire. In the tensile test, all fibers of the wire are under the same direction and stress condition. For this reason, American Society for Test and Materials (ASTM) prescribes the standard tensile test as 0.5 inch in diameter and 2 inch in focal distance. But the value of the results from this type of test is too large for

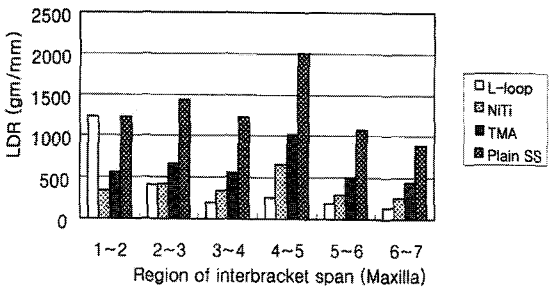


Fig. 7. The LDR in each interbracket region (Maxilla).

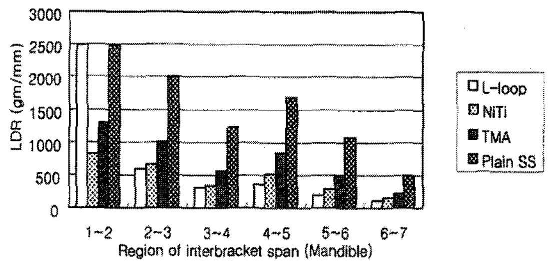


Fig. 8. The LDR in each interbracket region (Mandible).

the orthodontist to easily understand and apply to clinical practice. And in orthodontic practice, there are few situations for the wire to be activated in the direction of the long axis (compression and tension). Consequently, the American Dental Association (ADA)[16] specification, and the Korean Standards (KS)[17] prescribe that the mechanical properties of orthodontic wires should be presented by the cantilever bending tests(ADA specification No. 32, KS P 5314-1990). However, because the cantilever action of orthodontic wire is also very rare in practice, many orthodontic studies dealt with three point bending test or its modifications.[11,18,19] In this study, a modified cantilever test was used, in which the supporting end was fixed by the bracket and loading end was also engaged by the bracket moving upward. This type of method is different from a simple cantilever test, because, there is an extra bending effect in the loading end and friction between the bracket and wire. But this type of testing method can simulate more closely the situation of uprighting posterior teeth and changes the cant of occlusal plane (Fig. 6). For all those, this type of testing methods was accepted. For the same reasons, the closing direction of the loop was determined as the direction of activation.

3. The regional LDR in the interbracket span

As shown in Fig. 7 and 8, L-loops of a MEAW have different LDRs regionally; a high value for the anterior segment and a low value for the posterior segments due to the length of horizontal loops and the interbracket span. The region between the lateral incisor and the canine where the first loop of MEAW and the intermaxillary elastics are placed had the highest LDR in both arch, so it is possible to resist against the elastic force and transmit them anteriorly and posteriorly. The LDRs for all the L-loop are lower than those of other wires in every interbracket region except the region between the central and the lateral incisors. Table 6 shows that the ratios of the LDR for the L-loop to those of the NiTi, TMA, and plain stainless steel are on the average 1:1.53, 1:2.47, and 1:5.16, respectively. In this study, however, it was shown that MEAW in some regions of posterior interbracket area had an even larger LDR ratio of approximately 1:7 compared with that of a plain stainless steel wire. This finding seems to correspond to Kim's estimation in his study.[7]

It can be stated that while the difference between the LDR of the L-loop and that of NiTi in a long interbracket span was low, the difference was more significant in a short interbracket span (Table 6). That is to say that LDR of L-loop is less affected on the span than that of NiTi and TMA.

While the orthodontic wire engaged within the brackets offers an orthodontic force for tooth movement, it tends to restrict the individual tooth movement due to the continuity of arch wire. Through the breakage of the wire continuity with the loop, the tendency of the wire to restrict the various amounts and pattern of tooth movement can be relieved. In MEAW, therefore, at the region of short interbracket span, individual tooth movement is

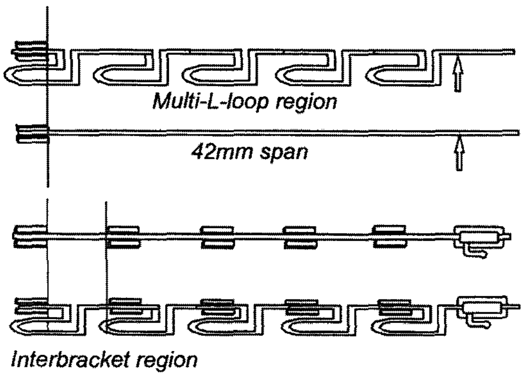


Fig. 9. The definition of the terms used in this study.

facilitated even more than in the case of NiTi and other plain wires.

4. The LDR of the multi-L-loop region of MEAW

In this study, the term 'multi-L-loop region' was used for the MEAW and the term '42mm span' for the plain wires including NiTi, TMA and stainless steel wire to describe the region from the distal border of lateral incisor's bracket to the mesial border of second molar's buccal tube (Fig. 9). Lee[3] measured the entire arch LDR of the MEAW and compared it with that of the wires of different materials. An upper MEAW's LDR ratio is 1:2.52 of a plain stainless steel, 1:0.49 of a Nitinol, and 1:0.80 of a TMA. In other words, LDR of the entire arch of a MEAW is somewhat stiffer than a TMA and twice as stiff as a Nitinol wire. Chun[4] who used the finite element analysis on the LDR of various wires obtained similar results as Lee's findings. In this study, only the posterior segment of MEAW including the 5 loops from lateral incisor to second molar was tested in order to compare the LDR of the entire posterior region of MEAW with that of other materials in the same length(42mm). In the multi-L-loop region, upper MEAW's LDR ratio was 1:3.19 of a plain stainless steel, 1:0.54 of a NiTi and 1:1.47 of a TMA wire. In the case of the lower MEAW, the ratio was slightly lower than one of upper MEAW, because the horizontal length of the loops are larger in the upper MEAW than in the lower MEAW (Table 8). The reason for the somewhat higher ratio than that of Lee's study[3] is that the stiff anterior part of MEAW was excluded in this study. According to these results, the multiloop region has slightly smaller stiffness than TMA, but has almost twice the stiffness of NiTi wire. This means that the elastic force applied to the first loop, between the lateral incisor and canine, can be transmitted more effectively to the posterior teeth in MEAW than in NiTi.

5. Consideration of the wire stiffness of MEAW

(1) Calculating the wire stiffness number

A simple numbering system was developed to describe the relative stiffness of wires based on cross section and the material.[10] The material stiffness number is based on the modulus of the elasticity of the material, which is the property that determines its stiffness. The material stiffness number of stainless steel used in orthodontic treatment was arbitrarily set at 1.0. The cross sectional stiffness number was set at 1.0 for 0.004 inch diameter round wire.

To compare the wire stiffness of L-loop with each of the various regions and the multi-L-loop region, the wire stiffness number was calculated according to the definition suggested by Burstone.[10]

(2) Wire stiffness number in each region

Table 9 shows the wire stiffness number of each region. In the cases of TMA and plain stainless steel wire, the wire stiffness number in the interbracket region is slightly higher than that in the 42mm span and relatively constant.

But in NiTi, the wire stiffness number of interbracket region was constantly 1.8 times larger than the 42mm span. In the case of the L-loop, on the contrary, the wire stiffness number of interbracket region was rather smaller than that of the multi-L-loop region and had large variation according to the region (Table 10).

In the test of the interbracket region, NiTi showed

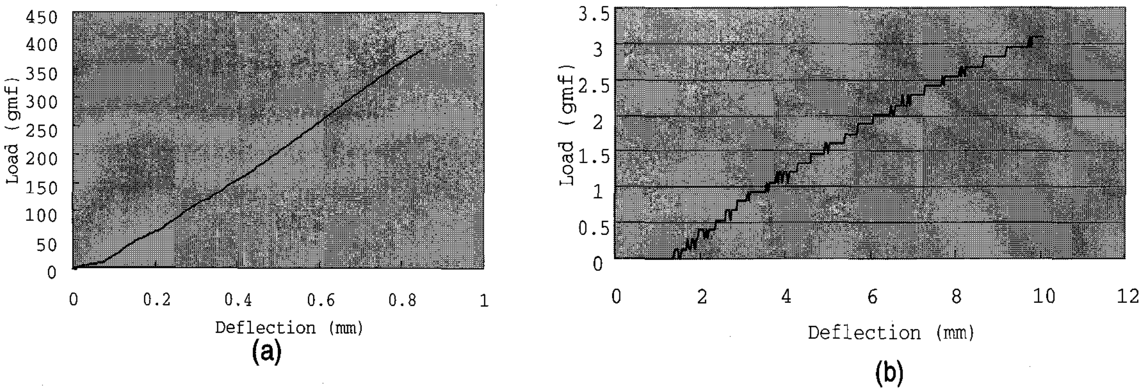


Fig. 10. Load deflection curve of NiTi: a) 5mm interbracket region, the linear relationship between load and deflection is recognized, b) 42mm span, the slope is slightly decreased according to the deflection.

the linear relationship between deflection and load in the range of 1mm deflection, but in the test of 42mm span, the slope showed the tendency to decrease in the range of 10mm deflection (Fig. 10). This is one of the characteristics of nickel titanium wires. In the stress strain curves of shape memory wires, such as the NiTi wire, the slope(i.e. stiffness) changes according to the amount of elastic deflection. The stiffness is relatively high at the initial deflection, but is significantly reduced with increased deflection. Stiffness or the LDR of NiTi, in other words, was measured differently according to the amount of deflection. In the experiment of the 42 mm span, the wires were deflected at the posterior end by 10mm in order to simulate actual clinical application of the MEAW. And the LDR, in 42 mm span test, was measured at a lower value. In the finishing stage of the treatment, however, the deflection range in the interbracket span, would not exceed 1.0 mm. Within the range of 1.0mm deflection, NiTi showed linear relationships between load and deflection. For this reason, the wire stiffness number of NiTi was larger in the interbracket region than in the 42mm span.

In the case of MEAW, the wire stiffness number of the interbracket region was smaller than that of the multi-L-loop region and had large variations according to the region. Differences in wire stiffness number between the interbracket region and the multi-L-loop region can be explained as follows. The LDR of L-loop in the interbracket span is not affected as much by length of span as in the cases of TMA and stainless steel wire. In other words, when the length of the span is decreased, the LDR does not increase in a significant manner as the other wires. While the wire segments engaged in the brackets do not contribute to lowering of the stiffness of the entire arch, the horizontal part of the L-loops can affect vertical elastic deflection, thus reducing stiffness. The length of the wire from the distal of the lateral incisor's bracket to the second molar tube is 42㎜ for the plain archwires and 104㎜ for the horizontal segments of the upper multi-L-loop. The widths of the four brackets in this region are added up to 13㎜. The ratio of the sum of the bracket slot widths to the length of the arch in this region is only 12.5% for MEAW, while it is as much as 31.0% for plain wires. For this reason, the wire stiffness of MEAW in the interbracket region is smaller than that in the multi-L-loop region (Fig. 11).

(3) Verifying the experimental results with the theoretically derived equation

The wire stiffness of a plain wire should be constant according to the length or the region.[10] But the wire stiffness of multi-L-loop was different from that of the single loop. Table 11 shows an example of an L-loop and multi-L- loops substituting the arbitrary length of the segment to the equation of

Table 11. Substituting the arbitrary length of the segment of L-loop to the equation of LDR*

The number of loops incorporated in the multi-loop wire	Horizontal length of the wire's base (mm)[1]	Theoretical values		
		LDR (gm/mm)	Wire stiffness (gm · mm^2)	Ratio of wire stiffness[2]
single loop	11	25.45	33871.53	1.00
two loops	22	4.10	43679.72	1.29
three loops	33	1.33	47774.38	1.41
four loops	44	0.59	50007.39	1.48
five loops	55	0.31	51410.98	1.52

[1] The length of each segment is as follows(mm) ; *a*=5, *b*=2.7, *c*=7.0, *d*=2.7, *e*=8.0, *f*=5.4, *g*=5.0, *l*=11

[2] Ratio of wire stiffness of each multiloop wire to single loop

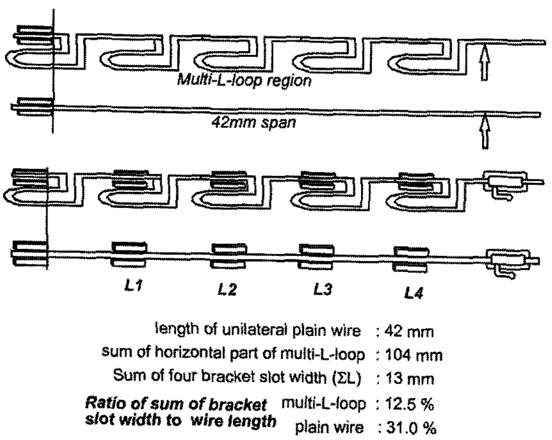


Fig. 11. Ratio of sum of bracket slot width to length of wire.

LDR. The more loops are incorporated in the multi-L-loop, the tendency for greater wire stiffness was observed, but with reduced increment in the wire stiffness. It seemed, furthermore, that the wire stiffness might converge at a certain level with increased the number of L-loops incorporated in the multi-L-loop.

As shown in table 11, in the case of a L-loop of which has a horizontal loop of 8mm and a base of 11mm in length, the wire stiffness is 0.66 times that of multi-L-loop composed of the five L-loops. This is one of the reason that the wire stiffness of MEAW in the interbracket region is smaller than that in the multi-L-loop region.

(4) Clinical implication of wire stiffness number of MEAW

Lee and Kim[20] showed in their photoelastic study that in the case of ideal archwire, the stress was concentrated in the anterior area, but in the case of the MEAW with tipback bend, the elastic forces were transmitted equally from the anterior area to the posterior teeth. This means that if all teeth could move simulateneously, orthodontic force should be transmitted effectively toward the posterior teeth. Lee and Nahm[6] compared MEAW with nickel titanium wire incorporated with the curve of Spee by finite element analysis, and found that in shape memory wire the amount of displacement at the region of the canine where the elastic force was applied, was greater than in MEAW. A result from Shin and Chang's study[21] showed, on the contrary, that the greater the Class II elastic force, the more stress was induced at the posterior teeth. And this tendency was more significant in ideal arch than in MEAW. The results of these two studies showed that arch wire should have some stiffness in order to transmit orthodontic force to the posterior teeth.

In this study, while the multi-L-loop region of MEAW is stiffer than that of NiTi wires, it is less stiff in the interbracket regions where the loops are incorporated. As demonstrated earlier, since the wire stiffness of the MEAW differs from region to region, each region of MEAW is equvalent to that of various sizes of stainless steel wires, from the view point of wire stiffness. As shown in Table 12, in the upper

Table 12. Conversion of the wire stiffness number of L-loop to the size of plain stainless steel wire with equivalent wire stiffness

Region(tooth number)	Span(mm)	L-loop (wire stiffness number)	Stainless steel wire with equivalent wire stiffness number(inch in diameter)
Maxilla			
1~2	6.0	634.93	0.0201
2~3	5.5	176.80	0.0146
3~4	6.0	10419	0.0128
4~5	4.5	73.32	0.0117
5~6	6.5	114.28	0.0131
6~7	7.0	101.93	0.0127
Multi-L-loop region	42.0	187.59	0.0148
Mandible			
1~2	4.0	571.27	0.0196
2~3	4.5	173.91	0.0145
3~4	6.0	156.66	0.0142
4~5	5.0	127.39	0.0134
5~6	6.5	114.28	0.0131
6~7	9.0	130.67	0.0135
Multi-L-loop region	42.0	200.91	0.0151

multi-L-loop region, MEAW is equivalent to 0.0148 inch round stainless steel wire, but in the region between the first and the second premolar, the L-loop has equivalent wire stiffness of 0.0117 inch round stainless steel wire. In the case of the MEAW, stiffiness of individual interbracket span can be calculated by setting wire stiffness number of multi-L- loop region at the value 1.0, as shown in Table 10. For instance, the anterior region without the loop has a high stiffness, making it possible for incisors to be adjusted as one unit. The first loop to which intermaxillary elastics are usually engaged is stiffer than other posterior. This prevents the orthodontic force generated by the elastics from concentrating in the region of the first loop and helps to distribute the force to other regions.

Low stiffness at the interbracket region also makes it possible to apply a low and constant force allowing the teeth to move in the directions applied by the MEAW. On the other hand, the high wire stiffness of the entire arch wire makes it possible to transmit orthodontic force effectively from the anterior to the posterior segments. Since there is no regional difference in the wire stiffness, the LDR of NiTi and TMA, in contrast, is determined by interbracket distance alone. In this instance, because the wire stiffness in the interbracket span is higher than that of the entire arch in NiTi, individual tooth movement is difficult and the transmission of the force is ineffective.

The mechanism of action of the MEAW has been examined in a photoelasticity study by Lee[20] and Matsui[22] and in a holographic study by Jin & Yang.[23] According to their observations, the MEAW was observed transmitting the force generated by intermaxillary elastics throughout the entire arch effectively. The results of this study confirmed their findings.

With further research like this one that analyzes the mechanics of MEAW, it will be possible to clarify the mechanism of the action of MEAW in greater detail, and also to modify the design of MEAW for improved mechanical properties.

CONCLUSIONS

In order to analyze the mechanical characteristics of multiloop edgewise archwire (MEAW), first, its load deflection rate (LDR) was compared with that of various other arch wires at the individual interbracket span. Second, the wire stiffness in the interbracket span was compared with that in the multi-L- loop region (the span from the distal border of the bracket of the lateral incisor to the mesial border of buccal tube of the second molar). Third, the experimental results were verified with the theoretically derived formula.

The L-loops of five different sizes and multi-L-loops for the upper and lower entire posterior region(multi-L-loop region) were made out of .016 ×.022 permachrome stainless steel wire. Five samples of each loop and the segments of stainless steel, TMA, and nickel titanium wires in .016×.022 size were obtained.

The LDRs of each wire in the interbracket span and the multi-L-loop region were measured using the Instron. The wire stiffness numbers of each condition were calculated. And the theoretical formula of LDR of multi-L-loop was derived.

The results were as follows :

1. The LDR of MEAW in the individual interbracket span was 1/1.53 of that of the NiTi, 1/2.47 of TMA and 1/5.16 of the plain stainless steel wire.
2. The wire stiffness of MEAW in the multi-L- loop region was 1.53 times greater than in the interbracket region, and its LDR was almost twice as large as that of NiTi in that region.
3. According to the theoretically derived equation, the wire stiffness of single L-loop is lower than that of multi-L-loop.

The results of this study suggested that MEAW had the unique mechanical property which could allow individual tooth movement and transmit the elastic force effectively through the entire arch wire.

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국문초록

Multiloop edgewise arch wire의 부위별 하중변형률

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본 연구는 multiloop edgewise arch wire(MEAW)의 기계적 특성을 분석하기 위해, 1) 개별 브라켓간 부위에서의 MEAW의 하중변형률을 수종의 재질로 된 동일 규격의 교정용 호선과 비교하고, 2)개별 브라켓간 부위와 multi-L-loop 부위(측절치 브라켓의 원심연과 제2대구치 튜브의 근심연간의 거리)에서의 wire stiffness를 비교하며, 3)단일 L-loop와 multi-L-loop의 하중변형률에 대한 공학적 이론식을 유도하여 MEAW의 하중변형특성을 규명하고자 시행하였다. 5가지의 서로 다른 수평길이를 지닌 L-loop와 5개의 L-loop로 구성된 상하악의 multi-L-loop를 .016×.022 inch의 stainless steel 강선으로 제작하였고, .016×.022 inch의 plain stainless steel, TMA, NiTi를 준비하였다. Instron model 4466 만능시험기에 50N 용량의 load cell을 부착하여 crosshead의 속도 1.0mm/분, 브라켓간 부위의 시험시에는 최대변위량 1.0mm로 각 브라켓간격에서 측정하였고, multi-L-loop부위의 경우는 최대변위량 10mm, 42mm의 거리에서 측정하였다. 반복된 실험에 의해 발생할 수 있는 응력에 따른 물리적 성질 변화의 가능성을 배제하기 위해 각 조건마다 동일한 5개의 시편을 사용하였다. 측정된 하중변형률과 각 실험의 브라켓간격을 이용하여 각 브라켓부위에서의 L-loop의 wire stiffness number를 계산하였고 이를 multi-L-loop의 그것과 비교하였다. 5개의 loop로 구성된 multi-L-loop를 35개의 직선구간으로 나누어 각 구간의 에너지를 계산, 총합을 낸 후 가해진 외력으로 미분하여 하중변형률의 이론식을 유도하였으며, 이를 wire stiffness로 환산하여 단일 L-loop의 wire stiffness와 비교하였다. 그 결과는 다음과 같았다. 1) 각 브라켓 간격에서의 L-loop의 하중변형률은 평균적으로 stainless steel wire의 1/5.16, NiTi의 1/1.53, TMA의 1/2.47이었다. 2) multi-L-loop부위에서의 MEAW의 wire stiffness는 개개 브라켓간 간격에서보다 평균 1.53배 더 높았고, 같은 부위에서의 NiTi보다 1.9배 더 높았다. 3) 유도된 하중변형률의 이론식에 따르면, 부위에 따라서 wire stiffness의 차이를 보이지 않는 직선 강선과는 달리, L-loop가 부여된 경우, 개별 L-loop의 wire stiffness는 전체 multi-L-loop의 wire stiffness보다 낮은 것으로 나타났다.

이상의 연구결과로 미루어 볼 때, MEAW는 개별적인 치아이동을 허용하면서, 가해진 교정력을 효과적으로 전체 치열로 전달할 수 있는 독특한 기계적 특성을 지니고 있는 것으로 생각된다.

주요 단어 : 부위별 하중변형률, wire stiffness, MEAW, TMA, NiTi