

# Nickel-Titanium Closed-coil Springs

## Evaluation of the clinical plateau

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*In this in vitro study, we tested 10 types of springs from 5 manufacturers. We performed a simulation of the clinically relevant action of the spring during its application and treatment of the patient. For determining the deactivation plateau, we developed an innovative statistical method, making it feasible to precisely find and evaluate the necessary clinically relevant parameters of all types of NiTi SE closed-coil springs in the market. In terms of the application simplicity, the 3M 12 and 3M 9 springs proved to be the most suitable.*

**Keywords:** Nickel-titanium, super-elastic, closed-coil spring, plateau

Nickel-titanium (NiTi) super-elastic (SE) closed-coil springs are used in fixed orthodontic treatment to move teeth. They are particularly useful when a wide working range under constant force is required, and NiTi springs close gaps faster and more fluently than do elastic modules [1-4].

Mechanical properties of a SE closed-coil spring depend on its design [5], *i.e.*, geometry, and its material [5], *i.e.*, type of NiTi alloy and its properties.

The uncommon features, for which the NiTi super-elastic (SE) closed-coil springs are distinguished, stem from the ability of the NiTi alloy to transformations the inner crystal structure between a martensitic phase (M, martensite) and an austenitic phase (A, austenite).

The deformation stress necessary for A-to-M transition is higher than the one needed for M-to-A transition under given strain. This phenomenon is called *mechanical hysteresis*. It applies also for transformations induced by temperature, when it is called *thermal hysteresis* [6-9].

A superelastic coil spring produces nearly constant force over a large range of deformations called the *plateau* [10]. The model stress-strain diagram (fig. 1) shows that there are actually two plateaus, one during activation (A-to-M) and one during deactivation (M-to-A). And since the super-elastic closed-coil springs are designed to pull (the tooth;

the spring is getting shorter), the crucial part from a clinician's point of view is the *deactivation plateau*, sometimes referred to as the clinical plateau [11], (M-to-A) (fig. 1, marked by crosses).

In clinical practice, the force measured during the *deactivation plateau* varies between NiTi closed-coil springs from various manufacturers, even if the nominal force levels are identical. Only some NiTi SE coil springs show a force-change during the deactivation lower than 50 g (0.491 N) [12,13]. Complicating matters further, the plateau is only found within certain extension or activation limits. Moreover, since the *deactivation plateau* is typically not flat, there is no consensus as to where the force level should be measured - at the start, at the middle or at the end of the plateau?

There are several suppliers offering various ranges of NiTi coil springs classified by the length of the spring and nominal force but only some of them declare the values of nominal forces exerted by the particular springs. Moreover, none of the suppliers provide all the deactivation plateau parameters (*i.e.*, max, min: force, spring extension, activation (spring) length; extension range; slope) necessary for orthodontists so they can make relevant decisions in clinical practice.

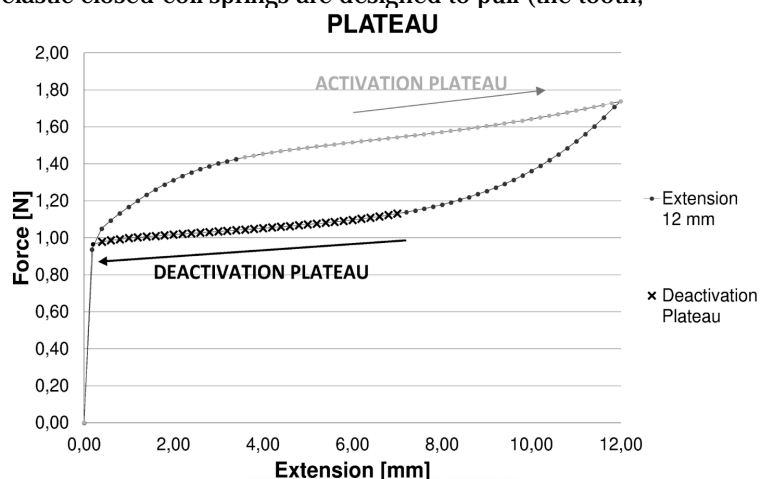


Fig. 1. A typical stress-strain curve for NiTi springs. The activation plateau is marked by gray dots. The deactivation plateau is marked by crosses.

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**Table 1**

LIST OF TESTED SPRING TYPES WITH AVAILABLE NOMINAL PARAMETERS. MAXIMUM EXTENSIONS OF THE SPRINGS DURING TESTING ARE LISTED IN THE COLUMN CYCLES MAXIMUM EXTENSION (mm). NOMINAL LENGTH (mm) REFERS TO THE INTER-EYELET DISTANCE DECLARED FOR THE SPECIFIC SPRING BY ITS MANUFACTURER. N/A MEANS THAT THE NOMINAL FORCE OF THE SPRING HAS NOT BEEN DECLARED BY ITS MANUFACTURER

Abbreviation	Manufacturer	Type	Catalog number	Nominal force (g)	Nominal length (mm)	Cycles maximum extension (mm)
3M 9	3M	Medium 200 g	344-200	200	9	12
	American					
AO 9	Orthodontics	0.030 in/0.76 mm	855-180	N/A	9	12
D b	Dentaurum	Tomas coil spring light (blue)	302-012-00	N/A	8	12
		Tomas coil spring medium (yellow)				
D y	Dentaurum		302-012-10	N/A	8	12
GAC L	GAC	Light (100 g)	10-000-03	100	9	12
GAC H	GAC	Heavy (200 g)	10-000-01	200	9	12
OO 9	Ortho Organizers	0.010x0.030 (200 g)	100-622	200	9	12
3M 12	3M	Medium 200 g	346-200	200	12	24
	American					
AO 12	Orthodontics	0.030 in/0.76 mm	855-181	N/A	12	24
OO 12	Ortho Organizers	0.010x0.030 (200 g)	100-623	200	12	24

Also, the current methods to determine and evaluate the deactivation plateau [11,14,15] have their substantial shortcomings. For instance, they do not allow to evaluate 1) springs with minimal mechanical hystereses, 2) springs that cannot achieve full transformation to the martensite state without damage, 3) springs with significantly unbalanced force curves in the vicinity of the deactivation plateau, or 4) springs with very large deactivation plateaus. The issues of evaluation methods and the determination of the parameters of the deactivation plateau (*i.e.*, force and extension range, slope of the force of the deactivation plateau - *force stability*) have not yet been successfully resolved. In clinical practice, this may result in a quite random choice of spring type, leading to the risk of applying a force that is either too low or too high.

The purpose of this study was to identify the parameters of the NiTi SE closed-coil springs' deactivation plateau mentioned above and the methodology of their evaluation to enable orthodontists to make relevant decisions in clinical practice.

## Experimental part

### Test springs

We tested ten different types of springs from five manufacturers (GAC, 3M, Dentaurum, OrthoOrganizers, AmericanOrthodontics) (table 1). For each type of spring, we performed a number of stability [16] and destructive tests to discover the optimal plateau phase deployment and measurement limits for safe spring operation. Fifteen samples of each spring type were tested.

### Test procedures

We performed a simulation of the clinically relevant action of the spring during its application and treatment of the patient. At a constant temperature of 37°C, the NiTi closed-coil springs were activated to their specific maximum extension for safe operation (table 1, *Cycles maximum extension* (mm)) and then deactivated back to their original spring length. During the test, we measured and recorded the applied force, the spring extension, and the ambient temperature.

### Test equipment

For testing, we used a Universal testing system Instron 3343 for measuring force and extension. The load frame

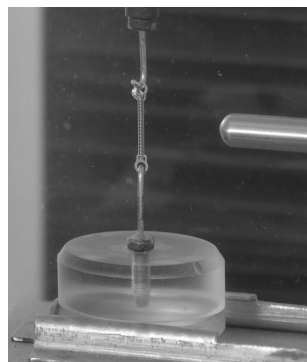


Fig. 2. Photo of testing equipment

was equipped with a  $\pm 10$  N static load cell (fig. 2). To maintain constant conditions of measurement, measuring appliances were terminated by hooks with sharp arches in order to prevent the springs from moving or rotating against the axis of measurement. A thermostatic water bath, into which the test coil springs were immersed during measurement, was controlled by a Julabo F 25 thermostat. The accuracy of the temperature set was  $\pm 0.1^\circ\text{C}$ .

### Statistical analysis

Measurement data were processed and statistically evaluated with the help of MS Excel 2007 (Microsoft Corp, Redmond WA, USA) and NCSS 2007 (Hintze, J. (2007). NCSS 2007. NCSS LLC, Kaysville, Utah, USA. [www.ncss.com](http://www.ncss.com)). We compared the individual spring parameters with selected corresponding parameter limits. We used D'Agostino Omnibus Test to test normality of the distribution for each spring parameter. Since for each tested parameter the normality of the distribution was rejected in at least one of the spring types, we opted for using the Wilcoxon Signed-Rank Test because it does not presuppose a normal distribution.

For determining and finding the deactivation plateaus, we used the following procedure, briefly described in the four step pictorial instruction (fig. 3) as well. We calculated the slopes among all pairs of consecutive measuring points in the deactivation part of the working curve. We found the maximum and minimum of the slopes. The obtained interval we then divided into a number of equally spaced subintervals. We chose six for the number of subintervals, because this proved to provide a good compromise between granularity and stability of results. From the slope

**Step 1:** measure extensions and forces *during deactivation*

**Step 2:** calculate slopes

	A	B	C
1	Extension (mm)	Force (N)	Slope (N/mm)
2	12,00047	3,69927	
3	12,00828	3,70034	
4	12,01203	3,70097	
5	11,84797	3,64658	0,331525052
6	11,61203	3,53706	0,46418581
7	11,40359	3,44906	0,422183842
8	11,20047	3,3698	0,390212682
9	10,99969	3,29502	0,372447455
10	10,80062	3,22477	0,352890943
11	10,59984	3,15743	0,335391971
12	10,39996	3,08707	0,317966017

**Step 3:** calculate MIN/MAX, divide in 6, make frequency distribution table of slopes

MIN	0,05422703
MAX	0,46418581
Bin	Frequency
0,122553	31
0,19088	9
0,259206	6
0,327533	4
0,395859	5
0,464186	2

**Step 4:** mark (X) all points with slopes smaller than marked limit as deactivation plateau

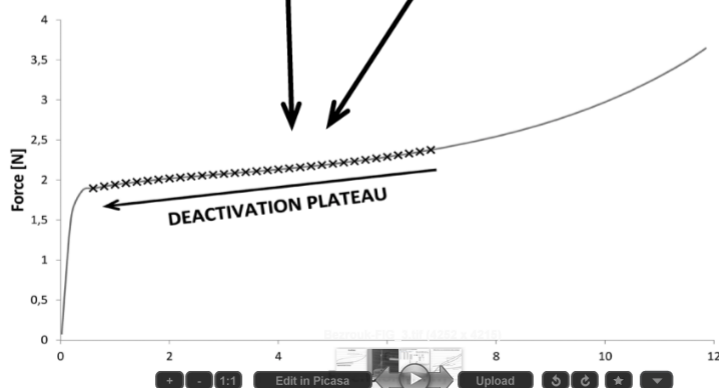


Fig. 3. Brief four step pictorial instruction describing the procedure for determining the deactivation plateau

dataset, we created a frequency distribution table using these subintervals. The subinterval containing the left-most local frequency maximum we call the *crucial interval*. If there were two consecutive subintervals with similar frequency values in maximum, we always chose the lower one. Then the measuring points considered to belong to the deactivation plateau are those whose slope to the next measuring point is equal to or less than the upper boundary of the crucial interval. Otherwise put, the plateau consists of all the measuring points contributing to the crucial interval or to the subintervals left from it. Consequently, the beginning of the deactivation plateau corresponds to the measuring point in the plateau area with the largest extension. The end of the deactivation plateau corresponds to the measuring point in the plateau area with the smallest extension. Applying linear regression, the slope of the curve's deactivation plateau was investigated, defined to be equal to the slope of the regression line.

## Results and discussions

### Evaluation of the deactivation plateau: general observations

Three different force curve types were observed during the measurements (fig. 4). The *GAC H* had a short minimum activation length necessary to reach its deactivation plateau, a relatively flat slope, a medium extension range of the deactivation plateau, and a large mechanical hysteresis. The *AO 9* had a large minimum activation length necessary to reach its deactivation plateau, a steep slope, a short extension range of the deactivation plateau, and a medium mechanical hysteresis. The *3M 9* had a short minimum activation length necessary to reach its deactivation plateau, a medium slope, a large extension range of the deactivation plateau, and a minimal mechanical hysteresis.

### Evaluation of the deactivation plateau: extension and activation range, force, force stability

The data show considerable inter-sample variability with respect to all the evaluated parameters of the deactivation plateau (i.e., extension and activation range, force, and force stability) (table 2).

The springs *GAC L*, *GAC H*, *OO 9*, *OO 12*, and *3M 12* had their respective nominal forces (as declared by the manufacturer, table 1) within the range of their deactivation plateau - Force (N); from to in table 2. The spring *3M 9* did not show its nominal force within the range of its deactivation plateau; the maximum force of its deactivation plateau - Force (N); to in table 2 - was significantly ( $p < 0.002$ ) below its nominal force. The springs *3M 9*, *3M 12*, *GAC L*, and *OO 9* showed their force falling significantly ( $p < 0.05$ ) below the nominal force (as declared by the manufacturer, table 1) within the deactivation plateau - Force (N); from in table 2. The nominal force was not specified by the manufacturer for the springs *AO 9*, *D b*, *D y*, and *AO 12* (table 1).

The *3M 9* had the shortest minimum spring extension (0.38 (0.38–0.40) mm) necessary to reach its deactivation plateau - Spring extension (mm); from in table 2. The springs *3M 9*, *3M 12*, *D y*, *GAC L*, and *GAC H* had minimum spring extensions significantly ( $p < 0.001$ ) below 1.00 mm. The springs *AO 9*, *OO 9*, *AO 12*, and *OO 12* had minimum spring extensions significantly ( $p < 0.002$ ) above 4.00 mm. The *OO 12* had the largest minimum spring extension (9.20 (8.60–9.40) mm).

The *D y* had the shortest minimum activation length (the distance between its two eyelets - Activation (spring) length (mm); from in table 2) necessary to reach its deactivation plateau (8.78 (8.78–8.80) mm). The springs *3M 9*, *D b*, *D y*, *GAC L*, and *GAC H* had minimum activation lengths significantly ( $p < 0.001$ ) below 10.00 mm. The

Table 2

DISCOVERED PARAMETERS OF DEACTIVATION PLATEAUS FOR INDIVIDUAL TESTED SPRINGS. THE USED NOTATION IS MEDIAN AND (Q1-Q3) (I.E., (1<sup>ST</sup> QUANTILE – 3<sup>RD</sup> QUANTILE)) AT THE LINE BELOW THE MEDIAN. FORCE (N); FROM” IS THE MINIMUM FORCE MEASURED WITHIN THE DEACTIVATION PLATEAU. FORCE (N); TO” IS THE MAXIMUM FORCE MEASURED WITHIN THE DEACTIVATION PLATEAU. ACTIVATION (SPRING) LENGTH (MM); FROM” IS THE MINIMUM DISTANCE BETWEEN THE TWO EYELETS OF THE SPRING MEASURED WITHIN THE DEACTIVATION PLATEAU. ACTIVATION (SPRING) LENGTH (MM); TO IS THE MAXIMUM DISTANCE BETWEEN THE TWO EYELETS OF THE SPRING MEASURED WITHIN THE DEACTIVATION PLATEAU. SPRING EXTENSION (MM); FROM IS THE MINIMUM EXTENSION OF THE SPRING MEASURED WITHIN THE DEACTIVATION PLATEAU. SPRING EXTENSION (MM); TO IS THE MAXIMUM EXTENSION OF THE SPRING MEASURED WITHIN THE DEACTIVATION PLATEAU

Abbreviation	DEACTIVATION PLATEAU							
	Force (N)		Activation (spring) length (mm)		Spring extension (mm)		Extension range (mm)	Slope (N·mm <sup>-1</sup> )
	from (Q1-Q3)	to (Q1-Q3)	from (Q1-Q3)	to (Q1-Q3)	from (Q1-Q3)	to (Q1-Q3)	(Q1-Q3)	(Q1-Q3)
3M 9	0.88 (0,87–0,95)	1.90 (1,86–1,95)	9.38 (9,38–9,40)	20.83 (20,83–20,83)	0.38 (0,38–0,40)	11.83 (11,83–11,83)	11.45 (11,25–11,45)	0.08 (0,08–0,08)
AO 9	2.25 (2,24–2,28)	3.29 (3,27–3,31)	13.20 (13,20–13,40)	17.80 (17,80–18,00)	4.20 (4,20–4,40)	8.80 (8,80–9,00)	4.60 (4,40–4,60)	0.22 (0,22–0,22)
D b	0.88 (0,87–0,90)	1.42 (1,41–1,43)	9.20 (9,18–9,38)	17.78 (17,58–17,78)	1.20 (1,18–1,38)	9.78 (9,58–9,78)	8.40 (8,40–8,60)	0.06 (0,06–0,06)
D y	1.20 (1,19–1,21)	1.57 (1,56–1,59)	8.78 (8,78–8,80)	14.58 (14,38–14,58)	0.78 (0,78–0,80)	6.58 (6,38–6,58)	5.80 (5,60–5,80)	0.06 (0,06–0,06)
GAC L	0.85 (0,83–0,86)	1.00 (0,99–1,01)	9.40 (9,40–9,40)	16.20 (16,20–16,20)	0.40 (0,40–0,40)	7.20 (7,20–7,20)	6.80 (6,80–6,80)	0.02 (0,02–0,02)
GAC H	1.95 (1,91–1,98)	2.45 (2,39–2,49)	9.60 (9,60–9,80)	15.80 (15,60–15,80)	0.60 (0,60–0,80)	6.80 (6,60–6,80)	6.00 (5,80–6,20)	0.08 (0,06–0,08)
OO 9	1.95 (1,93–1,97)	2.81 (2,79–2,83)	13.80 (13,60–13,80)	18.80 (18,80–18,80)	4.80 (4,60–4,80)	9.80 (9,80–9,80)	5.20 (5,00–5,20)	0.17 (0,16–0,17)
3M 12	1.02 (0,99–1,04)	2.06 (2,02–2,08)	12.40 (12,20–12,60)	35.21 (35,00–35,38)	0.40 (0,20–0,60)	23.21 (23,00–23,38)	22.81 (22,40–23,01)	0.04 (0,04–0,04)
AO 12	2.09 (2,06–2,11)	3.06 (3,03–3,09)	19.80 (19,60–20,00)	29.00 (28,80–29,00)	7.80 (7,60–8,00)	17.00 (16,80–17,00)	9.20 (9,00–9,40)	0.10 (0,10–0,11)
OO 12	1.96 (1,92–1,98)	2.83 (2,80–2,88)	21.20 (20,60–21,40)	30.60 (30,40–30,80)	9.20 (8,60–9,40)	18.60 (18,40–18,80)	9.40 (9,20–9,80)	0.09 (0,08–0,09)

springs AO 12 and OO 12 had minimum activation lengths significantly ( $p < 0.001$ ) above 19.00 mm. The OO 12 had the largest minimum activation length 21.20 (20.60–21.40) mm.

The 3M 12 had the largest extension range (22.81 (22.40–23.01) mm) of the deactivation plateau - Extension range (mm) in table 2. The springs 3M 12 and 3M 9 had their extension range of the deactivation plateau significantly ( $p < 0.001$ ) larger than 10 mm - Spring extension (mm); from to in table 2. The AO 9 had the shortest extension range (4.60 (4.40–4.60) mm) of the deactivation plateau.

The GAC L had the lowest slope (0.02 (0.02 – 0.02) Nmm<sup>-1</sup>) of the deactivation plateau - Slope (Nmm<sup>-1</sup>) in table 2. The AO 9 had the highest slope (0.22 (0.22–0.22) Nmm<sup>-1</sup>) of the deactivation plateau.

#### Evaluation of the springs

We tested 10 types of springs from 5 manufacturers under clinically relevant conditions. In this *in vitro* study, in terms of the application simplicity (i.e., ease of use), the 3M 12 and 3M 9 springs are the most suitable, i.e., they have sufficiently short minimum activation length, short minimum spring extension necessary to reach its deactivation plateau, and extension range of the deactivation plateau as large as possible.

For the spring 3M 9 there is a serious discrepancy between the declared nominal force value and the measured force value. For the springs AO 9, D b, D y, and AO 12, the nominal force has not been declared by the manufacturer.

We have developed a universal and objective statistical method for determining the deactivation plateau, making it feasible to precisely find and evaluate the necessary clinically relevant parameters of tested springs. And since the tested springs represents all types of NiTi super-elastic (SE) closed-coil springs (fig. 4), this evaluation method is applicable to all types of springs in the market. It overcomes the problems that beset current methods [11,14,15] of spring evaluation. The method can also be applied in specific cases such as springs with minimum mechanical hysteresis (e.g., 3M 9 in fig. 4), springs which cannot achieve full transformation to the martensite state without damage, or springs with significantly unbalanced force curves in the vicinity of the deactivation plateau (e.g., GAC H in fig. 4), or springs with a very large deactivation plateau (e.g., 3M 12 - Spring extension (mm); from to in table 2). It can even be applied for any desired maximum spring extension in cases where the force curve of the spring changes with the maximum extension of the spring (i.e., specifically springs with very large hysteresis - e.g., GAC H in fig. 4).

## Different force curve and deactivation plateau prototypes

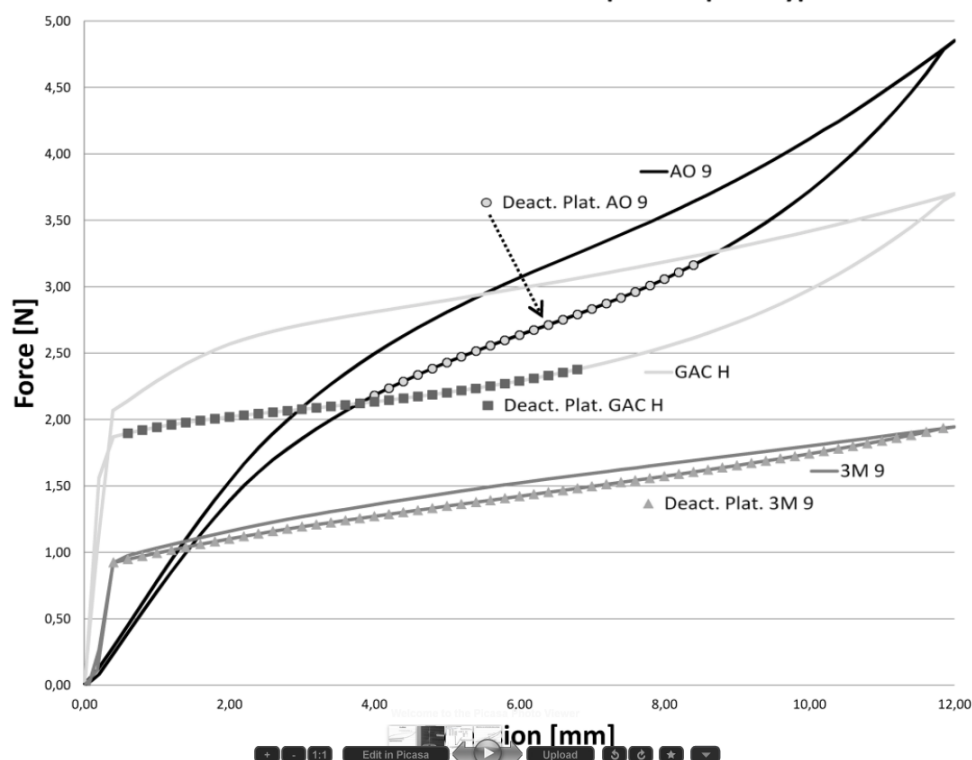


Fig. 4. Force curve and deactivation plateau prototypes. The light gray solid line indicates the GAC H-like force curve type. The square symbols indicate measuring points within the deactivation plateau of the GAC H-like force curve type. The black solid line indicates the AO 9-like force curve type. The circles mark measuring points within the deactivation plateau of the AO 9-like force curve type. The dark gray solid line indicates the 3M 9-like force curve type. The triangles show measuring points within the deactivation plateau of the 3M 9-like force curve type.

There are, however, certain limitations to our study. The study provides implications and conclusions for clinical practice based on *in vitro* observations of thermomechanical properties of nickel-titanium closed-coil springs, but it does not address the underlying causes of the thermomechanical properties, which are an issue for producers and material researchers rather than for a common orthodontist. The purpose of this study was to identify the parameters of the deactivation plateau of NiTi SE closed-coil springs and the methodology of their evaluation. Such information is crucial for orthodontists. However, it still needs to evaluate another crucial spring parameter—the hysteresis. Because only the springs with minor hysteresis and low temperature dependence of force can provide balanced action of forces and thus prevent adverse effects (e.g., root resorption) [17-20] resulting from the application of inadequate forces [21]. Moreover, all these results are valid also for the epoxy-coated springs because it was proved that a coating has no significant effect on mechanical properties of the NiTi wires [22] or springs [23]. Finally, to really fully enable orthodontists to make relevant decisions in clinical practice, it is necessary to develop a complex spring evaluation method and to define clinically important features of the closed-coil springs and the relevant spring parameters (*i.e.*, Safety, Patient comfort, Efficacy, Application simplicity, Reproducibility) for the purpose of this evaluation method. The spring hysteresis evaluation and the complex NiTi closed-coil springs' evaluation method *SPEAR*, we'll provide in the next part of this study.

## Conclusions

In this *in vitro* study, in terms of the application simplicity (*i.e.*, ease of use), the 3M 12 and 3M 9 springs are the most suitable, *i.e.*, they have sufficiently short minimum activation length, short minimum spring extension necessary to reach its deactivation plateau, and extension range of the deactivation plateau as large as possible.

We have developed a universal and objective statistical method for determining the deactivation plateau, making it feasible to precisely find and evaluate the necessary

clinically relevant parameters of all types of NiTi superelastic (SE) closed-coil springs in the market.

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## References

1. BARWART, O., The effect of temperature change on the load value of Japanese NiTi coil springs in the superelastic range. *Am J Orthod Dentofacial Orthop*, **110**, no. 5, 1996, p. 553-8.
2. BARWART, O., ROLLINGER, J.M., BURGER, A., An evaluation of the transition temperature range of super-elastic orthodontic NiTi springs using differential scanning calorimetry. *Eur J Orthod*, **21**, no. 5, 1999, p. 497-502.
3. BIERMANN, M.C., BERZINS, D.W., BRADLEY, T.G., Thermal analysis of as-received and clinically retrieved copper-nickel-titanium orthodontic archwires. *Angle Orthod*, **77**, no. 3, 2007, p. 499-503.
4. SANTORO, M., BESHES, D.N., Nickel-titanium alloys: Stress-related temperature transitional range. *Am J Orthod Dentofacial Orthop*, **118**, no. 6, 2000, p. 685-92.
5. ZAHORA, J., BEZROUK, A., HANUS, J., Models of stents - comparison and applications. *Physiol Res*, **56**, Suppl. 1, 2007, p. 115-21.
6. MELING, T.R., ODEGAARD, J., The effect of short-term temperature changes on the mechanical properties of rectangular nickel titanium archwires tested in torsion. *Angle Orthod*, **68**, no. 4, 1998, p. 369-76.
7. MELING, T.R., ODEGAARD, J., The effect of short-term temperature changes on superelastic nickel-titanium archwires activated in orthodontic bending. *Am J Orthod Dentofacial Orthop*, **119**, no. 3, 2001, p. 263-73.
8. MELING, T.R., ODEGAARD, J., The effect of temperature on the elastic responses to longitudinal torsion of rectangular nickel titanium archwires. *Angle Orthod*, **68**, no. 4, 1998, p. 357-68.
9. MELING, T.R., ODEGAARD, J., Short-term temperature changes influence the force exerted by superelastic nickel-titanium archwires activated in orthodontic bending. *Am J Orthod Dentofacial Orthop*, **114**, no. 5, 1998, p. 503-9.
10. ADLER, P., YU, W., PELTON, A., ZADNO, R., DUERIG, T., BARESI, R., On the tensile and torsional properties of pseudoelastic NiTi. *Scr Metall Mater*, **24**, no. 5, 1990, p. 943-7.

11. WICHELHAUS, A., BRAUCHLI, L., BALL, J., MERTMANN, M., Mechanical behavior and clinical application of nickel-titanium closed-coil springs under different stress levels and mechanical loading cycles. *Am J Orthod Dentofacial Orthop*, **137**, no. 5, 2010, p. 671-8.
12. LIU, S.S., KYUNG, H., BUSCHANG, P.H., Continuous forces are more effective than intermittent forces in expanding sutures. *Eur J Orthod*, **32**, no. 4, 2010, p. 371-80.
13. MAGANZINI, A.L., WONG, A.M., AHMED, M.K., Forces of various nickel titanium closed coil springs. *Angle Orthod*, **80**, no.1, 2010, p. 182-7.
14. MELSEN, B., TOPP, L.F., MELSEN, H.M., TERP, S., Force system developed from closed coil springs. *Eur J Orthod*, **16**, no. 6, 1994, p. 531-9.
15. SEGNER, D., IBE, D., Properties of superelastic wires and their relevance to orthodontic treatment. *Eur J Orthod*, **17**, no. 5, 1995, p. 395-402.
16. BEZROUK, A., BALSKEY, L., SMUTNY, M., et al., Thermo-mechanical properties of NiTi closed coil springs. —Force degradation and force regeneration over time, viscous properties. *Acta Medica (Hradec Kralove)*, **56**, no. 2, 2013, p. 41-6.
17. BREZNIAK, N., WASSERSTEIN, A., Root resorption after orthodontic treatment: Part 1. Literature review. *Am J Orthod Dentofacial Orthop*, **103**, no. 1, 1993, p. 62-6.
18. BREZNIAK, N., WASSERSTEIN, A., Root resorption after orthodontic treatment: Part 2. Literature review. *Am J Orthod Dentofacial Orthop*, **103**, no. 2, 1993, p. 138-46.
19. NAKANO, T., HOTOKEZAKA, H., HASHIMOTO, M., et al., Effects of different types of tooth movement and force magnitudes on the amount of tooth movement and root resorption in rats. *Angle Orthod*, **84**, no. 6, 2014, p.1079-85.
20. TOPKARA, A., KARAMAN, A.I., KAU, CH., Apical root resorption caused by orthodontic forces: A brief review and a long-term observation. *Eur J Dent*, **6**, no. 4, 2012, p. 445-53.
21. BEZROUK, A., BALSKEY, L., SMUTNY, M., et al., Thermomechanical properties of nickel-titanium closed-coil springs and their implications for clinical practice. *Am J Orthod Dentofacial Orthop*, **146**, no.3, 2014, p. 319-27.
22. POP, S.I., DUDESCU, M., BRATU, C., MERIE, V., PACURAR, M., Effect of Esthetic Coating on the Load Deflection and Surface Characteristics of the NiTi Orthodontic Archwires. *Rev Chim (Bucharest)*, **66**, no. 3, 2015, p.364
23. POP, S.I., BRATU, D.C., KONCZ, K., DUDESCU, M., ESIAN, D., SIMON, C., et al., Properties of the Epoxy-coated NiTi Open Coil Springs. *Rev Chim (Bucharest)*, **67**, no. 5, 2016, p. 1001

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