Giornale Italiano di Endodonzia (2015) 29, 58—64

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ORIGINAL ARTICLE/ARTICOLO ORIGINALE

Conditioning of root canal anatomy on static and dynamics of nickel-titanium rotary instruments

Condizionamento dell'anatomia canalare sulla statica e la dinamica degli strumenti rotanti in Nichel-Titanio

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Received 10 July 2015; accepted 28 July 2015
Available online 4 October 2015

KEYWORDS
Ni-Ti rotary instruments;
Rotary translation;
Roughness;
Torque;
Torsional stress.

Abstract
Aim: Aim of this study is to analyze the real movement, influenced by anatomical difficulties, of nickel-titanium rotary instruments within root canal systems; then the objective is to point out the physical and geometrical characteristics of an ideal instrument, able to overcome the most complex anatomies.
Methodology: At first, observation of the behavior of nickel-titanium rotary instruments within root canal systems and of the influence on them of root canal anatomy. Then, attempt to avoid the anatomical obstructions exploiting, with manual rotation, the advantages of a zero/low torque.

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Peer review under responsibility of Società Italiana di Endodonzia.

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http://dx.doi.org/10.1016/j.gien.2015.08.004

Results: Given that, in some root canals the severity of the curves prevents instruments to advance in rotation, we obtained significant results by manually advancing and rotating NiTi rotary instruments.
Conclusions: Therefore, in some cases, we would need an instrument that can reconcile efficiency with a reduction of mass and torque; the ideal instrument should have a very contained working part, combining efficiency with the decrease of mass and, consequently, of torsional stresses too.

PAROLE CHIAVE
Roto-traslazione;
Rugosità;
Stress torsionale;
Strumenti rotanti in Ni-Ti;
Torque.

Riassunto
Obiettivi: obiettivo di questo studio è di registrare il reale movimento degli strumenti, condizionato dalle difficoltà anatomiche, all'interno dei sistemi endocanalari, per poi tentare di evidenziare le caratteristiche fisiche e geometriche dello strumento ideale, impegnato ad affrontare le anatomie più complesse.
Materiali e Metodi: in un primo momento: osservazione del comportamento delle lime endodontiche meccaniche in Ni-Ti all'interno dei sistemi canalari e del condizionamento che l'anatomia canalare ha su di esse. In seguito: tentativo di eludere l'impedimento anatomico sfruttando, con la rotazione manuale, i vantaggi di un torque nullo-basso.
Risultati: premesso che in alcuni canali la severità delle curve impedisce agli strumenti di avanzare in rotazione, si sono ottenuti risultati significativi facendo avanzare e ruotare gli strumenti manualmente.
Conclusioni: alla luce di queste considerazioni, in alcuni casi avremmo bisogno di uno strumento che possa conciliare l'efficienza con una diminuzione di massa e torque. L'ideale sarebbe trovare uno strumento con parte lavorante molto contenuta e che coniughi, quindi, l'efficienza alla diminuzione della massa e di conseguenza anche dello stress torsionale.

Introduction

Anatomical complexities submit nickel-titanium (Ni-Ti) rotary instruments to stresses that often undermine their structural integrity. Despite an extraordinary development of Ni-Ti in more than 20 years of utilization, the increased risk of a separation remains a significant problem for many clinicians.[1] Many variable might contribute to this fracture, but the two main causes are cyclic fatigue and torsional fatigue, both of which might contribute to fracture, depending on canal curvature, instrument geometry and manufacturing method.[2–4] Torsional fracture occurs when an instrument tip or another part of the instrument is locked in a canal, while the shank continues to rotate and the elastic limit of the metal is exceeded[1,5]; instruments fractured by fatigue do not bind in the canal but they rotate freely around a curve, generating tension/compression cycles at the point of maximum flexure until fracture occurs.[6] Many fracture simulation studies on Ni-Ti instruments have been conducted separately from cyclic fatigue and torsional failure tests.[7,8] Only a few studies have tried to correlate these two factors of fracture.[9–12]

The endodontic handpiece imparts to the instruments a rotary motion around an axis (axis of the handpiece). When the apical portion of an instrument is inserted into a curvature, this portion will rotate around a new and different axis (axis of the canal after the curvature); this rotational motion around a new axis is the result of two actions; the first due to the structural continuity of the instrument which tends to transfer, to its portion inserted into the curvature, the same rotary motion imprinted by the endodontic handpiece to the portion of instrument in direct contact with the endodontic handpiece itself (rotation motion around the axis of the handpiece); the second due to the root canal walls, which, opposing the penetration of the instrument inserted into the curvature, exert on it pressing forces (this portion of instrument, in fact, attempts to rotate around the axis of the handpiece, but "slams" on root canal walls). The resultant of these two actions will rotate the portion of instrument inserted into the curvature around a new axis (axis of the canal after the curvature). To appreciate this rotation around a new and different axis, a rotary instrument can be put in rotation on a glass plate, in order to simulate a true rotation in a root canal with a high degree of curvature; a rotary-translation of the bent portion of the instrument can be observed; this would be impossible to value if root canal walls were present.[1]

Even when on the handpiece is not set any torque, once the instrument is inserted in the root canal, on it act forces (conditioning of the root canal walls) that flex it and give it the same root canal's shape.

Pressing forces exerted by root canal walls, if on one hand deviate the axis of rotation of the portion on instrument inserted in the curvature, on the other cause the increasing of friction forces that oppose the rotation and the advancement of the instrument. In vivo, when the curvatures are more than one, this phenomenon happens at every curve. Pressing forces (frictional forces), increase, up to the result of the inability to rotate and/or advance the endodontic file.

Today we have particularly efficient instruments that, cutting a lot, advance until reaching the apical foramen

[1] https://www.youtube.com/watch?v=RkGOftLEv1g.

(easily, most of the time). Therefore, the problem of the torsion is removed and instruments seems to break only for accumulation of cyclic fatigue. In fact, studies have found cyclic fatigue to be the primary cause of instrument fracture. It accounted for 50–90% of the mechanical failures.[13] However, it is unlikely that cyclic fatigue can occur if a rotating instrument does not significantly contact canal walls. Consequently, cyclic fatigue is not necessarily the main reason for instrument failure.[1] These considerations bring renewed emphasis on torsional stress as cause of fracture: there is torsion, more or less significant, whenever there is a curvature. However, the underlying physical principles of rotary root canal instrumentation are not fully understood nor researched; likewise, there is no concise norm for cyclic fatigue tests.[1]

The aim of this study is to highlight the behavior of Ni-Ti rotary files inside root canals and bring back the attention on torsional stress, partially forgotten since the cutting ability allows instruments to rapidly advance and gain the apex.

Materials and methods

As already mentioned, pressing forces generate frictional forces, which oppose the relative motion of rotation and advancement of the endodontic instruments. These frictional forces are much stronger than the greater are the forces that press one surface on the other and the greater is the roughness of the two surfaces in contact. Formula of sliding friction force:

$$Fa = \mu \times Fp$$

where Fa is the force of friction, μ is the coefficient of friction (static or dynamic) which is directly proportional to the roughness of surfaces in contact; Fp is the pressing force.

The relationships, which describe the forces acting on the instrument according with the curvature that it assumes in its various points are expressed below, where: E is the Young's modulus of the material, I is its moment of inertia, P is the force that exert the walls, x is the distance between the point of application of force and any point X of the instrument, d^2v/dx^2 is the curvature (that is the inverse of the radius of curvature) at a point x, $M(x)$ is the flexing moment at a point x (i.e. the force P per the arm x), $v(x)$ is the displacement compared to the 'axis of the handpiece of a point x of the instrument, theta (x) is the angle between the axis of the instrument and the axis of the handpiece at a point X. Fig. 1 shows a section of the instrument, forces exerted by walls are radial.

Flexing moment in x:

$$Mx = Px$$

$$\frac{d^2v(x)}{dx^2} = \frac{Px}{EI}$$

$$\frac{dv(x)}{dx} = \frac{Px^2}{2EI} + C1$$

$$v(x) = \frac{Px^3}{6EI} + C1x + C2$$

In the point of load application:

$$v0 = \frac{1PL^3}{3EI}$$

$$\theta 0 = \frac{1PL^2}{2EI}$$

Formulas show that in a point X of the instrument the curvature-shape, taken by the instrument, is greater how much is the force (P) exerted by root canal walls.

We observe that endodontic instruments made of particular Ni-Ti alloys (more "malleable" after thermal and mechanical treatments), after a rotation in a root canal with particularly severe curvatures, appear deformed by torsion after the impact with canal walls. A "softer" instrument when takes contact with root canal walls during the rotation tends to deform, losing "roughness"; so it has certainly a greater ability to advance, but a smaller cutting capacity. As well, a less malleable instrument, which does not tend to deform in contact with root canal walls, will be more efficient, but will accumulate rapidly torsion fatigue. Endodontic instruments with superior cutting ability and untreated Ni-Ti alloys (harder), non-deformable in contact with root canal walls, in analog angles undergo smaller deformations and, in one sense, less report the presence of natural torsional stress. The latter are more cleansing, the first deform and make minor cleansing, burnishing but less cutting, root canal walls: so the instrument will reach the apical foramen, but organic and inorganic debris will be coated on the walls. In fact, we know that the most efficient cleaning is obtained by the cutting action of the endodontic instruments.[14]

We noticed that in some complex root canal anatomies (Figs. 2 and 3), inside of which, in mechanical rotation, endodontic files appear to be rejected and, in manual rotation, they could cover the entire canal length. By using rotary Ni-Ti instruments manually, we apply minimum values of torque and angular acceleration, often allowing the endodontic file to overcome the anatomical obstacle (Figs. 4–6). With manual rotation the change of axis of rotation starts in a less abrupt and more gradual way. The light push toward apical direction, contextual to manual rotation, compatibly

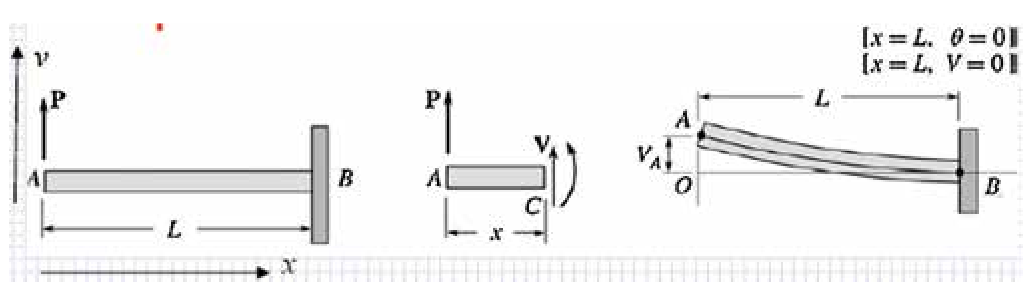

Figure 1 Free-fixed beam.

Figure 2 Initial RX, showing the necessity of a root canal treatment on 1.7. Apparent resorption of DB root.

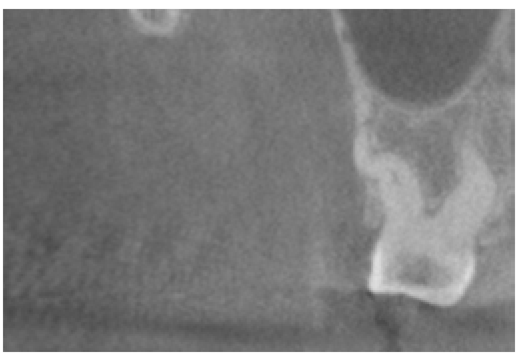

Figure 3 CB-CT image showing the S-shaped anatomy of DB root.

Figure 4 Final RX, filling of root canal system of 1.7.

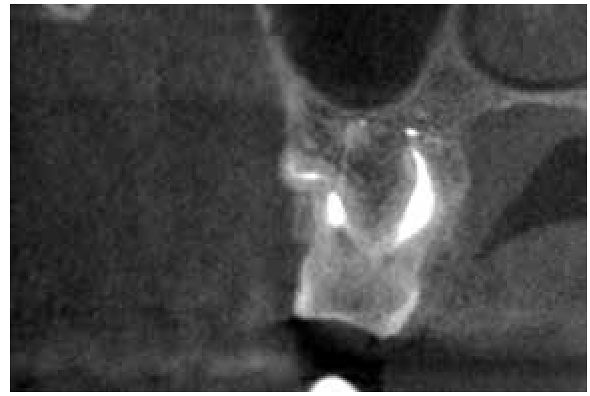

Figure 5 CB-CT images showing how the S-shaped anatomy of DB root has been entirely cleaned, shaped (with Ni-Ti rotary instruments used in manual rotation), then filled.

Figure 6 3D image of the filled root canal systems.

Figure 7 Initial RX of 4.6.

with size and roughness of the instrument (as a matter of low roughness and small sizes, we used MTwo- Sweden & Martina, Padova, Italy), will anticipate the rotary-translation and, at the same time, the generated impact on root canal's walls; this impact produces frictions, which prevents the instrument from advancing. In addition, many authors reported that reduction in operational speed could prevent taper locking, deformation and fracturing of Ni-Ti instruments[15–17] during clinical practice.

Figure 8 Mesial root canal system's high degree of curvature.

Figure 9 Final RX.

Figure 10 One-year follow-up.

In this other case (Fig. 7), we can see how in a root canal with high degree of curvature in the apical one-third (Fig. 8), which prevents the engine-driven instruments to advance in rotation, as said, by manual rotation the entire working length can be shaped (Figs. 9 and 10).

Results

So, we need to contain friction forces; to do this we can modify the characteristics of endodontic instruments, decreasing their roughness or reducing pressing forces between the instrument and root canal walls. For example, we should study instruments with a very contained working part and significantly reduced cutting efficiency in the coronal portion, in order to decrease roughness of its sections in contact. This instrument could be used after a preliminary enlargement with conventional rotary instruments, brought in proximity of the anatomical complication. As seen, the geometrical design is an important determinant because of the effect on the torsional and bending properties of the instrument.[19] In fact, the mechanical properties of the instruments are clearly influenced by their geometrical configurations, which include the cross-sectional shape (which determine the bending and torsional inertia), taper, helical angle and pitch.[20]

However, from the above, another fundamental element that we can modify to reduce the friction is to decrease pressing forces, for example, by reducing the torque on the endodontic motor. In fact, the higher is the torque set at the orifice of root canal (torque set on the endodontic motor), the greater is the reaction (and thus the pressing force) that we receive from the canal walls: thus, decreasing the momentum on the handpiece, the intensity of frictional forces will be reduced.

$$T = f \times b$$

where T is the torque, f is the intensity of the pair of forces applied from the handpiece to the instrument, and b is the arm or the distance between the two forces. Hence, reducing T, for the same arm, decreases the intensity of the forces applied from the handpiece and, therefore, decreases the intensity of pressing forces. The amount of torque generated clearly depends on the size of the contact areas between the instruments and the canal walls, as was demonstrated.[21]

Ni-Ti engine-files operate by way of continuous rotation in the root canal and, as such, are subjected to unidirectional torque (assuming no stalling).[2] The value of torsional (shear) stress varies depending on the canal size,[22,23] hardness of the dentine to be cut,[24] and the use of a lubricant.[25] The cross-sectional configuration is also an important determinant of the distribution of stresses on the instrument.[26]

In some cases, therefore, the only way to advance is to reduce torque, but the minimum value of torque selectable in most endodontic motor is 1 N/m; a low value, but not negligible in absolute and still too high for circumvent the anatomical impediment. Friction, therefore, decrease either reducing the torque of the endodontic motor, or by making a less wrinkled endodontic instrument (limiting/containing its working part), in such a way that its portion located at the point of maximum curvature, takes minimum contacts with root canal walls (better zero contacts), simulating what occurs in vitro with cyclic fatigue tests. To date, several torque-controlled low-speed motors have been introduced to help reduce the incidence of separation when using rotary instruments.[1] The efficacy and clinical rationale for using these torque-controlled motors has been described recently in a case report.[27]

One of the effects of the real movement of rotary endodontic instruments into root canal systems is that the file will go across a longer way than that of a steel file, used, at first, to determine working length. So much so that, if we refer the working length measured with an hand file on a rotary file, once it is rotating, when the rubber stopper, representing the established working length, arrives in correspondence of the chosen point of reference, the apex locator often does not confirm this data; but it will be necessary another small advancement to get the real working length. This process would be particularly valuable as much severe will be the curves that rotary instrument has to face and much less root canal system will be relatively straight and wide its transverse diameter; reason why we would need always apex locator to be connected to the rotary file during root canal shaping.

Discussion

Since we know the real movement of Ni-Ti rotary file in root canals, we can now understand the importance of torsional stress and controlled torque for clinic practice. In fact, in the clinical situation, because of the diversity of canal dimensions, Ni-Ti rotary instruments may be subject to torsional stress of varying degrees, especially at the early stage of canal enlargement.[28]

We know that cyclic fatigue tests are performed without torque: in this case, the instrument does not keep contact with canal walls. In fact, in cyclic fatigue tests[29] files were rotated freely without tip binding, which limits the stress on the files to that produced by flexural stress. Moreover, torsional or lateral loading of the instrument as may be experienced in the clinical situation is not reproduced in much test method.[30] Furthermore, the few documented studies on torsional moments and forces exerted during actual canal preparation were carried out using straight canals.[1]

Clinically, cyclic fatigue fracture seems to be more prevalent in curved root canals, whereas torsional failure might occur even in a straight canal.[3,31] Although both failure modes probably occur simultaneously during root canal shaping,[32] most laboratory studies of instrument separation have been conducted separately either for cyclic fatigue resistance or torsional failure,[3,7,18,31,33–35] probably for convenience or for better control of the loading condition. There were rare studies that correlated these two aspects of fracture.[28]

In vivo, as soon as the rotary file takes contact with the walls of a curvature, because of the friction that comes from the pressing forces, it twists and struggles to advance: the progress of the rotation will be strongly slowed. If we rely only on the results of cyclic fatigue tests, we could use a new endodontic instrument respecting the time limits that are provided by manufacturers. However, in vivo, that data could point out only the flexibility of the instrument, but those times are not respected because we have to consider, in addition to simple rotating bending, also torsional fatigue, that cannot be evaluated in vitro. Therefore, we have to take special care because, in particular situations, we could have sudden and unexpected breakage that we actually had to expect: Ni-Ti rotary files are susceptible to fracture, especially when they are used in curved root canals in continuous rotation.[34]

Particularly, when an endodontic instrument has to face a 90° curvature, the torque set on the endodontic handpiece is equal to that of resistance, so the instrument cannot advance because the propulsion it receives is equal and opposite to the force, that prevents its progression.

At every curvature, in fact, the most apical part of the instrument, as seen, changes its axis of rotation and its rotation become a rotatory-translation that, because of the presence of root canal walls, turns into torsion. Therefore, we should talk about accumulation of torsional fatigue, because the instruments are subject to torsional forces, that are greater the more extensive and numerous are the angles of the curvature. In addition, more sharp an instrument is, the greater are its contacts with root canal walls, more it will be subject to torsional stresses, thus to accumulation of torsional fatigue. The endodontic instrument is subjected to torsion, its progression slows down and, because of the accumulation of fatigue (cyclic and torsional), it can undergo breakage.

Torsional overload is an important cause of failure for an endodontic instrument and should never be forgotten or underestimated. Therefore, it is easy to understand the importance to study a technique or an endodontic instrument, which can relate this phenomenon and allow a safe endodontic treatment according to root canal anatomy.

Conclusions

We have seen how anatomical complexities make very intricate the real movement of rotary instruments into root canal systems. Besides, we have seen that the mechanical rotation is actually a rotary-translation.

That is the reason why, in some cases, we would need an endodontic instrument that can reconcile efficiency with a reduction of working part and torque. The ideal would be to find an instrument:

- With few, minimal radial contact points and working part limited to the finishing touch and negotiation of apical one-third.
- Very sharp in order to keep down the value of torque.

Conflict of interest

The authors have no conflict of interest to declare.

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