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Historical Aspects and Evolution of Ligation and Appliances

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INTRODUCTION

The vast majority of fixed orthodontic appliances have stored tooth-moving forces in archwires which are deformed within their elastic limit. For this force to be transmitted to a tooth, wires need a form of connection to the bracket which is in turn fixed to the tooth. This connection has for many years been referred to as 'ligation' because the early forms of connection were most frequently a type of ligature and this remained the situation for several decades. All more recent forms of connection between bracket and archwire have retained the title of ligation. 'Elastomeric ligatures' and 'self-ligating brackets' are firmly established orthodontic terms. This chapter aims to outline the history and development of archwire ligation and to put self-ligation into this perspective.

EARLY LIGATURES

The earliest ligatures were often made from silk which had long been used in surgery for suturing. When stainless steel became available, this was universally adopted. Stainless steel ligatures have several inherent qualities. They are cheap, robust, essentially free from deformation and degradation and to an extent they can be applied tightly or loosely to the archwire. They also permit ligation of the archwire at a distance from the bracket. This distant ligation is particularly useful if the appliance tends to employ high forces from the archwires, because this high force prevents sensible full archwire engagement with significantly irregular teeth. Ironically, as will be discussed later, wire ligatures have contributed to such higher forces through the friction they generate. In spite of these good qualities and their widespread use over many decades, wire ligatures have substantial drawbacks and the most immediately apparent of these is the length of time required to place and remove the ligatures. One typical study[1] found that an additional 11 minutes was required to remove and replace two archwires if wire ligatures were used rather than elastomeric ligatures. Additional potential hazards include those arising from puncture wounds from the ligature ends and trauma to the patients' mucosa if the ligature end becomes displaced.

ELASTOMERIC LIGATURES

Elastomeric ligatures became available in the late 1960s and rapidly became the most common means of ligation, almost entirely because of the greatly reduced time required to place and remove them when compared with steel wire ligatures. It was also easier to learn the skills required to place these ligatures, so new clinicians and staff greatly preferred elastomerics. Intermaxillary elastics had been employed since the late nineteenth century, pioneered by well-known orthodontists such as Calvin S. Case and H.A. Baker. Initially these elastic bands were made from natural rubber but production of elastomeric chains and ligatures followed the ability to produce synthetic elastics from polyester or polyether urethanes. The ease of use and speed of placement of elastomeric ligatures did, however, lead to other definite disadvantages being generally overlooked, although readily apparent. Elastomerics frequently fail to fully engage an archwire when full engagement is intended. Twin brackets with the ability to 'figure of 8' the elastomerics are a significant help in this respect, but at the cost of greatly increased friction (*vide infra*). A recent paper by Khambay *et al.*[2] quantified the potential seating forces with wire and elastic ligatures and clearly showed the much higher archwire seating forces available with tight wire ligatures. A second and well-documented drawback with elastomerics is the substantial degradation of their mechanical properties in the oral environment. A comprehensive literature review of elastomeric chains[3] gives a good account of the relevant data and a more recent article[4] discusses the underlying reasons and clinical significance of this loss of mechanical properties. Typically elastomeric chains and ligatures suffer more than 50% degradation in force in the first 24 hours[5] when tested under *in vitro* experimental environments. The higher temperature in the mouth, enzymatic activity and lipid absorption by polyurethanes are all cited as *in vivo* sources of force relaxation. This leads to the well-known potential for elastomeric ligatures to fail to achieve or to maintain full archwire engagement in the bracket. Fig. 1.1 shows the familiar loss of rotational control of canines during space closure whilst the molar teeth have retained excellent archwire control through their rigid molar tubes. Fig. 1.2 shows a generalized loss of rotational control due to these shortcomings. Twin brackets with the ability to 'figure of 8' the elastomerics are a significant help in this respect but certainly not a complete answer.

A further factor of potential clinical importance is the variability in mechanical properties of elastomerics. This is well described by Lam *et al.*[6] who reported substantial variation in the range and tensile strength of elastomerics from different manufacturers and for different colours of elastomeric from the same manufacturer.

Lastly, there is a large body of literature to demonstrate the much higher friction between bracket and archwire *in vitro* with elastomeric ligation compared to wire ligatures. This had been proposed as a factor of clinical significance more than 30 years ago[7]. A recent and representative study which demonstrates this difference in friction well is by Hain *et al.*[8] The potential importance of friction and its relation to forms of ligation will be discussed in more detail below.

The great popularity of elastomeric ligation in the last 40 years was achieved in spite of these substantial deficiencies in relation to wire ligatures. Speed and ease of use was the over-riding asset of elastomerics and it is no surprise that the strongest motivation behind the early efforts to produce a satisfactory self-ligating bracket was a desire to have all the benefits of wire ligation but in addition to have a system which was quick and easy to use.

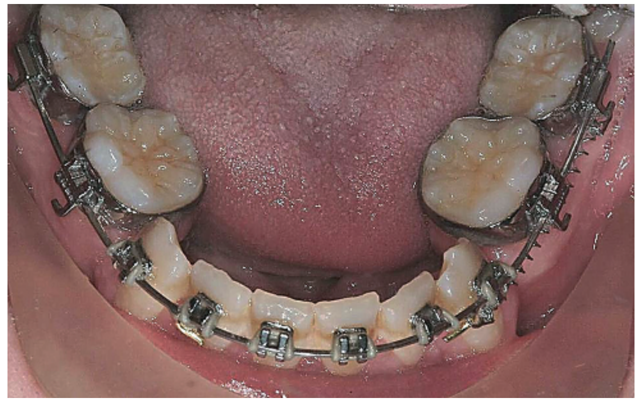


Fig. 1.1 Conventional elastomeric ligatures failing to maintain full bracket engagement on three of the six ligated teeth.

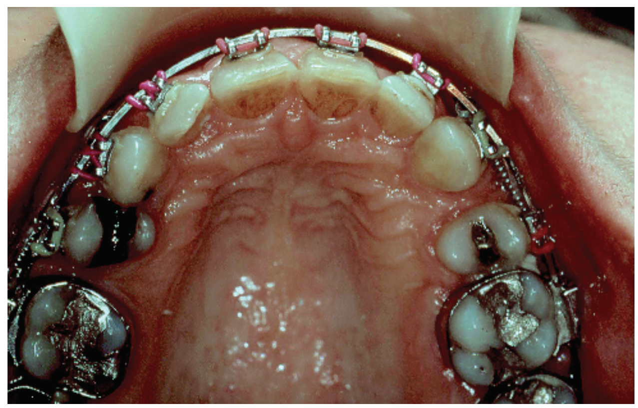


Fig. 1.2 Loss of rotational control by elastomeric ligatures on five teeth.

BEGG PINS

In the 1950s, Raymond Begg, a former pupil of Edward Angle, developed his light wire technique using Angle's ribbon arch brackets with round wire archwires[9]. A key feature of the technique was the use of brass pins as the method of ligation. These pins constituted the fourth (gingival) wall of the bracket slot and formed a rigid metal wall analogous in some ways to that of a molar tube or a self-ligating bracket. The pins were designed with shoulders to keep from binding the archwire in the early alignment stages and as 'hook-pins' they held the archwire in a more precise vertical position when thicker wires and auxiliaries were added later in the treatment. This author used many such pins, being trained simultaneously in Begg and edgewise mechanics during his initial specialist training. Begg pins had none of the disadvantages of elastomeric rings and were probably more rapid to place and remove than wire ligatures. These pins cannot be assessed in complete isolation from the rest of the Begg technique, but, in relation to self-ligation, it is well worth noting the reputation that the Begg technique acquired for rapid early alignment and the effectiveness of lighter forces when there was no friction from tight engagement with elastomerics to be overcome. As a footnote in orthodontic history, it should be recalled that self-ligating Begg brackets were produced in the 1970s and were used by this author on a number of cases. They had an inbuilt pin which was rotated into position over the archwire with the intention being to further simplify and speed the process of ligation. This development was overtaken by the development of better overall bracket systems in the 1970s – most notably the straight-wire appliance. Interestingly, when the tip-edge appliance was developed to be a successor to the Begg technique, it abandoned the metal, low-friction form of ligation which Begg pins represented and reverted to elastomerics.

SELF-LIGATION

Self-ligating orthodontic brackets have a relatively long history, but their development can best be viewed against the background of an almost universal use of elastomeric ligatures in spite of the known advantages of wire ligatures – and in a different context, of brass Begg pins. Elastomeric ligation gives unreliable archwire control, high friction, and an added oral hygiene challenge, although no data is available to indicate that conventional ligation results in more microbial attachment to appliances compared to their self-ligating counterparts. Wire ligation is better in every respect, but is very slow, inconsistent in its force application and the wire ends can cause trauma to patient and operator. It is easy to find examples of the deficiencies of conventional ligation, but clinicians have become accustomed to tolerating these shortcomings. Self-ligation offers the opportunity for very substantial improvements in relation to all of these drawbacks, but for many years remained the choice of a small minority of clinicians.

Self-ligating brackets by definition do not require an elastic or wire ligature, but have an inbuilt mechanism which can be opened and closed to secure the archwire. In the overwhelming majority of designs, this mechanism is a metal face to the bracket slot which is opened and closed with an instrument or finger tip. Brackets of this type have existed for a surprisingly long time in orthodontics – the Russell Lock edgewise attachment being described by Stolzenberg[11] in 1935. This was by modern standards a very primitive mechanism consisting of a labial grub-screw to retain the archwire. Many designs have been patented although only a minority has become commercially available. Table 1.1 is not

Table 1.1 Examples of self-ligating bracket designs.

Self-ligating bracket	Year
Russell Lock	1935
Ormco Edgelok	1972
Forestadent Mobil-Lock	1980
Forestadent Begg	1980
Strite Industries SPEED	1980
'A' Company Activa	1986
Adenta Time	1996
'A' Company Damon SL	1996
Ormco TwinLock	1998
Ormco/'A' Co. Damon2	2000
GAC In-Ovation	2000
Gestenco Oyster	2001
GAC In-Ovation R	2002
Adenta Evolution LT	2002
Forestadent lingual	2002
Ultradent OPAL	2004
Ormco Damon3	2004
3M Unitek Smartclip	2004
Ormco Damon 3 MX	2005
GAC In-Ovation L	2005
Ultradent OPAL metal	2006
Forestadent Quick	2006
Lancer Praxis Glide	2006
Class 1/Ortho Organisers Carrière LX	2006
GAC In-Ovation C	2006
Clarity SL	2007
American Orthodontics Vision LP	2007

exhaustive but includes a majority of the brackets produced commercially since that time. New designs continued to appear, notably the SPEED bracket (Strite Industries Ltd, 298 Shepherd Avenue, Cambridge, Ontario, N3C 1V1 Canada) in 1980. The Time bracket (Adenta GmbH, Gliching, Germany) becoming available in 1994, the Damon SL bracket ('A' Company, San Diego, California) in 1996 and the TwinLock bracket ('A' Company, San Diego, California) in 1998, were three representative designs from that decade. Since the turn of the century, the pace of development has greatly accelerated with the launch of at least 16 new brackets and rapidly increasing sales for such brackets. An overview of the status of self-ligation early in the current decade[12] summarizes the situation at that time. Recent years have seen a continuation of rapid changes in bracket technology, an expansion of the advocated advantages and a much greater research effort to gather the related evidence.

Proposed core advantages of self-ligating brackets

In the last two decades, a consensus has emerged on the potential core advantages of self-ligation. These can be summarized as: faster archwire removal and ligation, more certain full archwire engagement, less or no chairside assistance and low friction between bracket and archwire

Faster ligation

This should be discussed first because historically, it was the most powerful incentive to develop self-ligating brackets in the era of wire ligation. The relative slowness of wire ligation has already been noted[1]. Several studies have also shown that self-ligation offers savings in chairside time compared to elastomeric ligation. One relatively early study[13] found a 10 minute saving in time when comparing the removal and replacement of ligation on just the anterior 12 teeth in a pair of archwires.

Secure archwire engagement

It seems self-evident that a solid, reliable and robust form of ligation which cannot break or suffer decay in its ligating force is a desirable characteristic. Self-ligating brackets have varied in their robustness and reliability but several current brackets have mechanisms which deliver this advantage and the consequent enhanced control of tooth position.

Low friction

Wire ligatures produce substantially lower friction forces than elastomerics[1]. However, the forces generated by wire ligation still reach high and very variable levels[2] relative to those force levels which are thought to be optimal for tooth movement. There is now a large body of work detailing the very low levels of friction available with self-ligating brackets *in vitro*. Much of the earlier work was on brackets aligned in a passive configuration relative to the archwire. These all showed a dramatic reduction in friction with self-ligating brackets, especially those with passive slides. A representative paper[14] is from 1998. Fig. 1.3 shows the frictional resistance with four brackets and increasing wire sizes. For the passive self-ligating bracket (Damon SL) no friction was detectable until the wire is 0.019″/0.025″. The self-ligating bracket with the active clip (Adenta Time) has rather more friction but this is still very much less than the friction with 'A' Company standard Straight-Wire brackets and TP Tip-Edge brackets, both of which were ligated with elastomerics ligatures. A typical study[15] found that the friction per bracket was 41–61 g (depending on the archwire) with conventional brackets and conventional ligation and 3.6–15 g with Damon brackets. However, it was readily apparent that, *in vivo*, the archwires are active in varying degrees and directions and that this will add substantially to the resistance to sliding. Many more recent experimental designs have therefore investigated the effect of archwire activation on resistance to sliding.

Three papers by Thorstenson and Kusy in this area are particularly recommended[16–18]. In 2001, these authors examined the effects of varying active tip (angulation) on the resistance to sliding. They found that angulation beyond the angle at which the archwire first contacts the diagonally opposite corners of the bracket slot causes a similar rise in resistance to sliding of both self-ligated (Damon SL) and conventional brackets. However, at all degrees of tip, the Damon brackets produced significantly less resistance to sliding (Table 1.2). At a realistic angulation of 6° for a 0.018″ × 0.025″ stainless steel

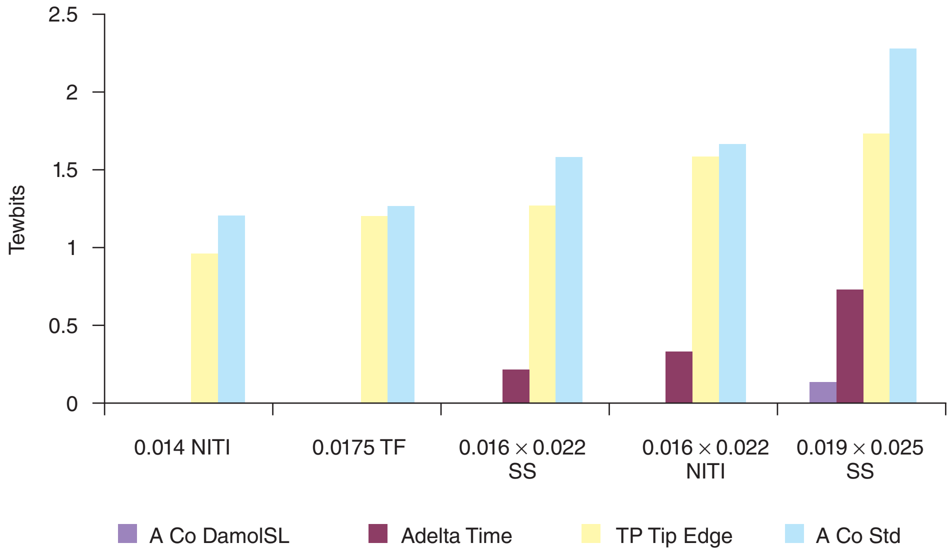


Fig. 1.3 Data from Thomas *et al.* (1998)[14] showing the typically very low friction for self-ligating brackets when compared to conventional ligation.

Table 1.2 Resistance to sliding (RS) for different bracket angulations with a 0.018/0.025 archwire. Forces in cN. Data from Thorstenson and Kusy (2001)[16].

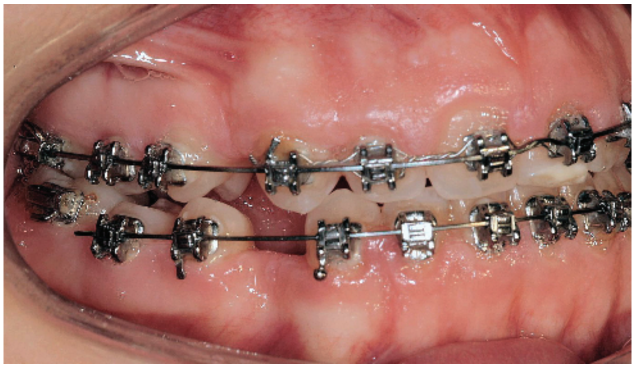
Angulation (degrees)	Damon SL	Conventional bracket
0	0	34
3.5	0	55
6.0	80	140

Table 1.3 Mean dynamic friction for different brackets with an applied tipping moment on a 0.019/0.025 stainless steel archwire. Forces in cN. Data from Mah *et al.* (2003)[19].

Bracket	Minitwin	Transcend 600	In-Ovation	Damon2
RS in cN	379	455	238	99

wire, the difference of 60 g is very probably of clinical significance. The second paper[17] compared different self-ligating brackets for resistance to sliding with active angulations. It quantifies a little more closely the lower resistance to sliding with passive self-ligation and points out that low resistance to tooth movement can also lead to unanticipated movement. The third paper[18] examined the same factors with wires of different sizes and in the dry state. The increase in friction when larger wires deflect the clips in active self-ligating brackets is quantified and the scanning electron micrographs of the different brackets show very clearly the relationship between small and large wires and active clips and passive slides. Table 1.3 contains data from another study[19] in which a known tipping (angulation) moment was applied to brackets able to tip up to 20° and the resistance to sliding was termed dynamic friction and measured for the four bracket types. The reduced friction for both types of self-ligating bracket can be seen and the difference between In-Ovation (active clip) and Damon2 (passive slide) was statistically and probably clinically significant. The study supports the view that self-ligation – and particularly passive self-ligation – produces substantially less resistance to tooth movement along an archwire even when the additional archwire activations found *in vivo* are present. Clinically, the low friction is very evident from the need with self-ligation to place a stop on all archwires to prevent the strong tendency for the archwire to slide through the brackets and traumatize the mucosa distally (Fig. 1.4).

Friction must be overcome for the majority of tooth movements to occur. Such movements include leveling, bucco-lingual alignment, rotation, correction of angulation, opening of space and any space closure with sliding mechanics. Frictional forces arising from the method of ligation are one source of the resistance to this relative movement between archwire and bracket. Correspondingly higher forces must therefore be applied to overcome this resistance and this has two related potential effects which inhibit tooth movement. Firstly, the net effective force is much harder to assess and is more likely to be undesirably higher than levels best suited to create the optimal histological response. Secondly, the binding forces are higher both between bracket and



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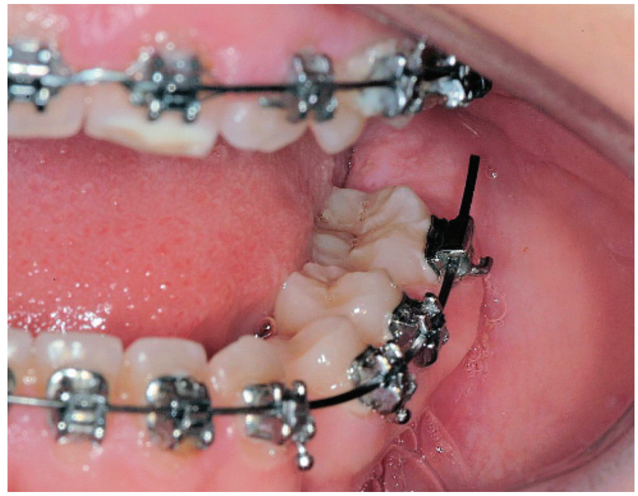

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Fig. 1.4 (a, b) An 0.018”/0.025” nickel–titanium wire displaced to the patient’s left (Damon2 brackets). This is a frequent unwanted result of the low friction with self-ligating brackets if no stop is placed on the archwire.

wire and also at the contacts between irregular adjacent teeth. These binding forces also inhibit the required relative movement between bracket and wire. Only a few tooth movements such as space closure with closing loops placed in the space, expansion of a well-aligned arch, and torque (inclination) changes are not influenced by a low-friction method of ligation.

Assistance to good oral hygiene?

Bacterial accumulation has been proposed as a potential disadvantage of elastomeric ligatures and whilst there is some evidence which points in this direction, there is non-confirmatory or contradictory evidence which makes this as yet undetermined. It is a prevalent anecdotal view that elastomerics accumulate plaque more than do wire ligatures and there is some evidence to support this[20]. There is also some evidence that wire ligatures reduce bleeding on probing of the gingival crevice when compared with elastomerics[21]. However, a scanning electron microscopy study[22] found no difference in bacterial morphotypes when using elastomerics or steel ligatures. Several further studies are in progress, but as yet, there is no evidence to support the proposed microbiological advantages.

More comfortable treatment?

It has been proposed that the lower forces and less friction will result in less discomfort for the patient. Two recent studies from the same centre have investigated this. In one study[23] Damon3 brackets were found to give the same discomfort as conventionally ligated Synthesis brackets. The other study[24] found no difference between SmartClip and conventionally ligated Victory brackets between patient visits, but a marked increase in discomfort when removing archwires through the Smartclip clips. Differences in design of specific self-ligating brackets can have important consequences. Miles *et al.*[25] did report lower discomfort initially but higher discomfort at a later stage with Damon2 brackets, but overall, there is currently little evidence that self-ligation is beneficial in this respect.

The core list of the advantages now has a fairly solid experimental basis, with better, more refined evidence appearing at frequent intervals. These advantages apply in principle to all self-ligating brackets although the different types of bracket may vary in their ability to deliver them consistently in practice. Advantages have also been proposed as resulting from the unique combination of low friction and good control which only self-ligating brackets (or molar tubes) can provide.

Secure archwire engagement and low friction as a combination

Other bracket types – most notably Begg brackets – have achieved low friction by virtue of an extremely loose fit between a round archwire and a very narrow bracket, but this is at the cost of making full control of tooth position correspondingly more difficult. Some brackets with an edgewise slot have incorporated shoulders to distance the elastomeric from the archwire and thus reduce friction, but this type of design also produces reduced friction at the expense of reduced control. With tie-wing brackets, an improvement in control is usually at the cost of an increase in friction, especially with elastomeric ligatures. This point has been very nicely illustrated by Matasa[26]. The combination of very low friction and very secure full archwire engagement in an edgewise-type slot is currently only possible with self-ligating brackets (or with molar tubes). It has therefore been proposed[12] that this combination enables a tooth to slide easily along an archwire with lower and more predictable net forces and yet under complete control, with almost none of the undesirable rotation of the tooth resulting from a deformable mode of ligation such as an elastomeric. Sliding mechanics to move individual teeth is therefore a more attractive form of mechanics.

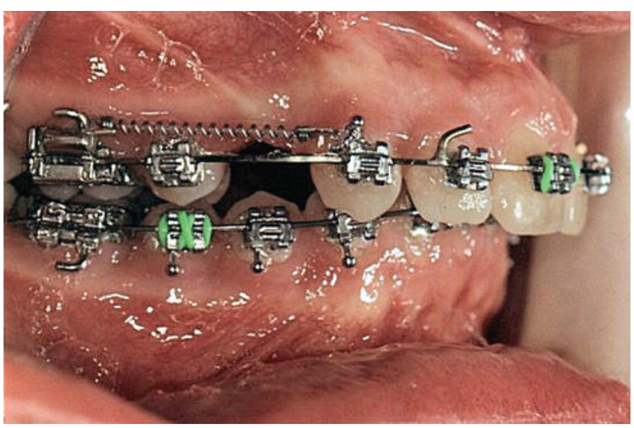
Possible anchorage consequences of the combination of low friction and secure full archwire engagement

Tooth movement has been shown in beagle dogs to be only partially related to the level of force applied[27]. In clinical investigations[28], extremely good anchorage preservation has been shown where retraction of individual canine teeth was pitted against an anchorage unit of the rest of the arch. This study using conventional brackets supports the clinical application of the differential force theory but use of this anchorage-preserving effect is inhibited by the tendency with conventional ligation for individual teeth to rotate when retracted along an archwire and then require realignment. Fig. 1.5 shows a clinical example of canine retraction with Damon SL brackets and undetectable anchorage loss. The hypothesis that self-ligation may increase available anchorage is therefore based on three possibilities: lower friction encourages the use of lighter forces which the differential force theory suggests would enhance anchorage preservation; individual teeth, e.g. canines, can be moved with no loss of rotational control; and faster treatment means less mesial drift and perhaps better co-operation? This proposal is handicapped by the current inconclusive evidence that treatment is faster with self-ligation.

All three of these proposals are plausible and in line with general anchorage theory, but currently lack robust and direct supporting evidence. These considerations apply equally to preservation of anterior anchorage in hypodontia cases where movement of individual teeth along an archwire is frequently required.

Alignment of severely irregular teeth

Crowded teeth have to push each other along the archwire to gain alignment. A combination of low



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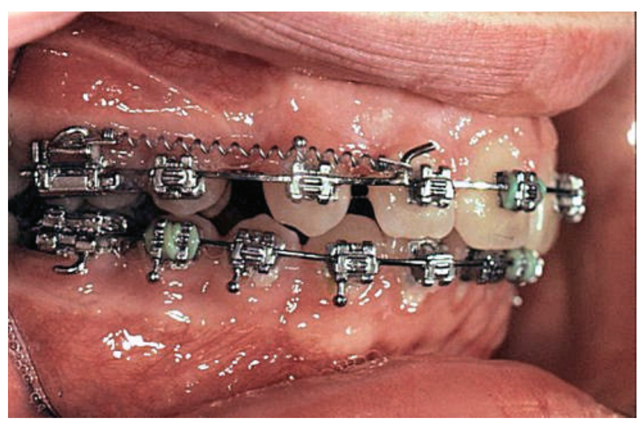

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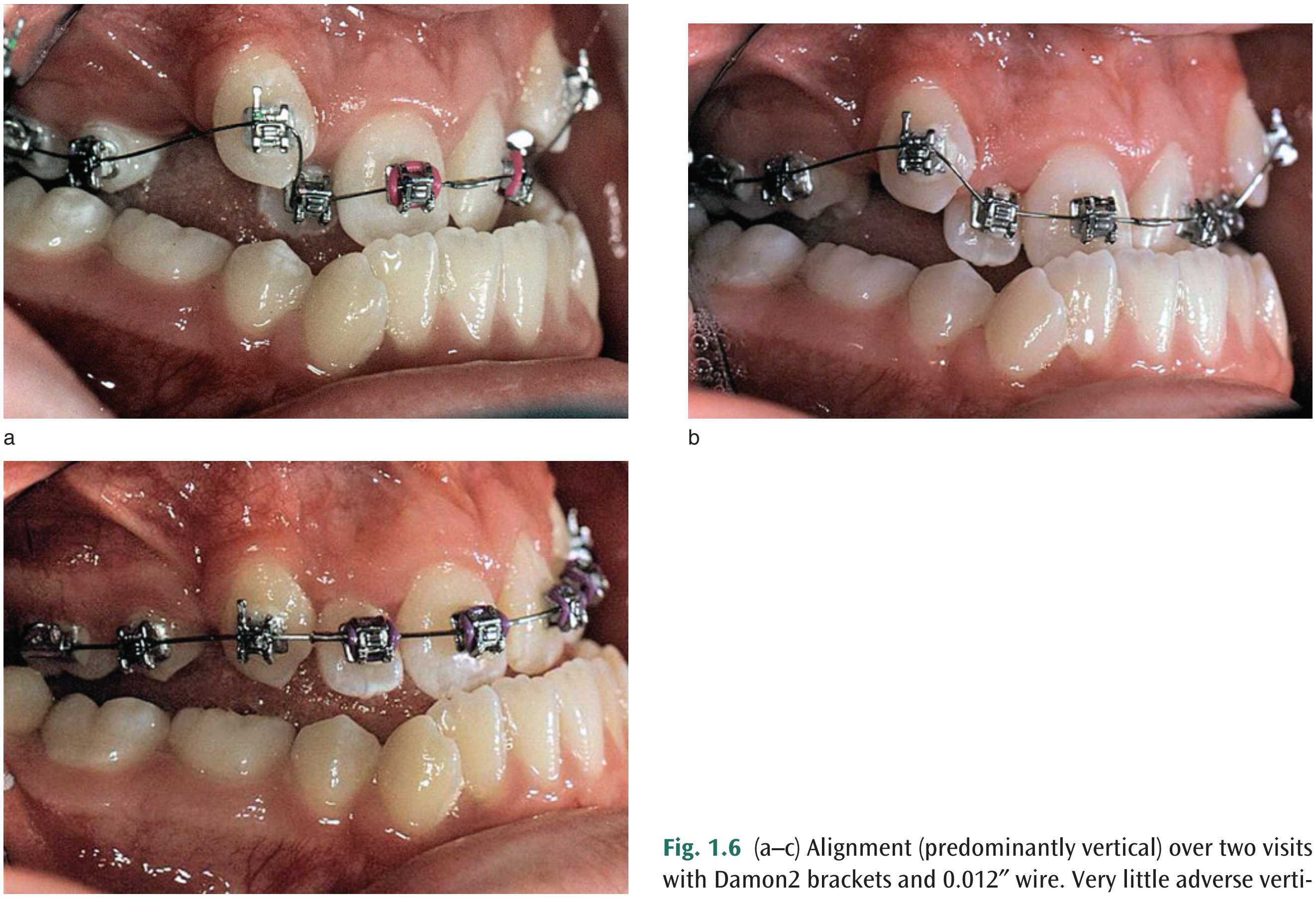
Fig. 1.5 (a, b) Retraction of an individual canine tooth with Damon SL self-ligating brackets on a 0.019”/0.025” stainless steel wire. No loss of anchorage or loss of rotational control of the canine is detectable.



a b c

Fig. 1.6 (a–c) Alignment (predominantly vertical) over two visits with Damon2 brackets and 0.012″ wire. Very little adverse vertical movement of the central incisors is seen.

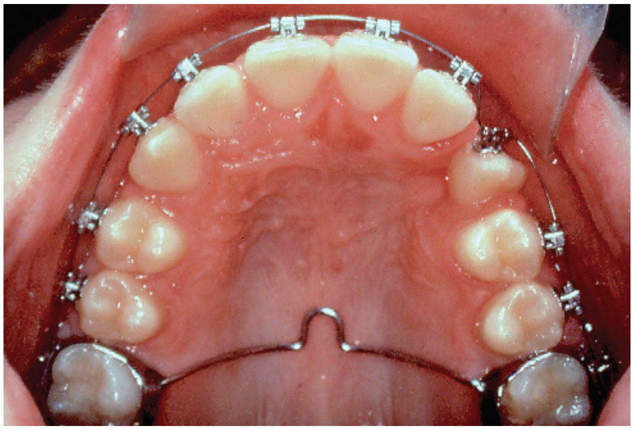
friction and secure full engagement should be particularly useful through enabling the wire to release from binding and slide through the adjacent brackets. This easy release of binding also serves to minimize adverse reciprocal tooth movements (Fig. 1.6). The relationship between friction and derotation has been described and quantified[29] and the potential adverse forces were shown to be very large. Fig. 1.7 shows the results of one visit derotating a tooth. Low friction should therefore facilitate rapid alignment whilst the secure bracket engagement permits full engagement and good control with severely displaced teeth. The evidence relating self-ligation to speed of alignment will be discussed later in this chapter.

Factors which have hindered the adoption of self-ligation

It is interesting and instructive to consider why, in spite of the potential advantages, self-ligation has for so long and until so recently been a small part of orthodontics. In part this has been the result of imperfections in bracket performance. These imperfections have varied with different bracket designs and can be illustrated by examples from Table 1.1. The author of this chapter has used 15 of the types in this table.

In the opinion of this author, an ideal self-ligating bracket should deliver the core advantages already discussed and in addition should:

- Be very easy to open and close with low forces applied to the teeth during these procedures and with all archwire sizes and materials
- Never open inadvertently, allowing loss of tooth control
- Have a ligating mechanism that never jams or breaks or distorts or changes in its performance through the treatment period
- Have a positively held open clip/slide position, so that the clip or slide does not obstruct the view of



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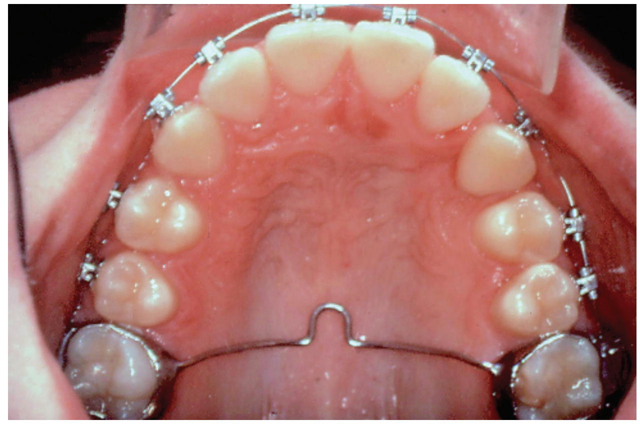

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Fig. 1.7 (a, b) One visit of derotation of an upper canine on 0.012″ wire and Activa self-ligating brackets. The inevitable initial bracket binding is able to release and pass the surplus archwire through the adjacent brackets as the tooth derotates.

the bracket slot or the actual placement of the archwire

- Be tolerant of a reasonable excess of composite material without obstructing the clip/slide mechanism
- Permit easy attachment and removal of all the usual auxiliary components of an appliance, such as elastomeric chain, undertie ligatures, laceback ligatures, without interfering with the self-ligating clip/slide
- Permit easy placement and removal of hooks/posts and possibly other auxiliaries on the brackets. With the security of self-ligation, the use of elastics directly to a bracket is much more frequently appropriate than with conventional ligation
- Have a suitably narrow mesio-distal dimension to take advantage of the secure archwire engagement and permit large interbracket spans.
- Have the performance expected of all orthodontic brackets in terms of bond strength and smoothness of contour

Many brackets have been less than satisfactory in several of these requirements and a representative selection can be used to illustrate the difficulties experienced over the years in producing the ideal bracket.

Edgelok brackets[30] (Ormco Corporation, 1717 W. Collins Ave., Orange, CA 92867) were the first self-ligating bracket to be produced in significant quantities. Disadvantages included inadequate rotational control, bulkiness and some inconvenience with opening and closing the slide and they were never widely adopted.

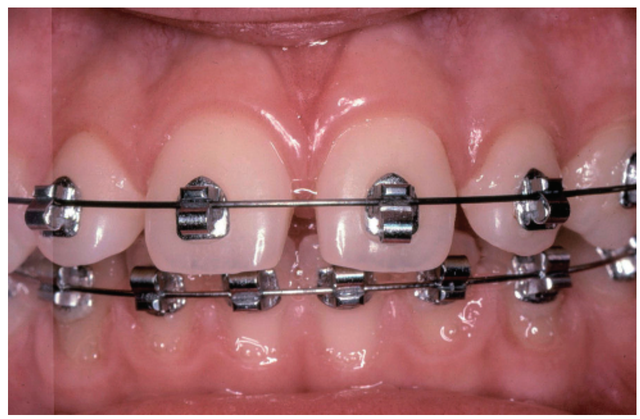


Fig. 1.8 Early example of a SPEED bracket. The bracket contained no retaining slot for the spring clip which led to spring distortion and loss of archwire control. A retaining slot was later incorporated.

The well known **SPEED brackets**[31] have remained in successful production since 1980. This testifies to the inherent soundness of many of the original design features. Early brackets (Fig. 1.8) were handicapped by clips which could too easily be displaced or distorted. These drawbacks have since been successfully addressed by improvements in the bracket body and in the clip itself, but combined with the inherent unfamiliarity for clinicians of a bracket with no tie wings, these aspects probably hindered the wider popularity of SPEED in previous years.

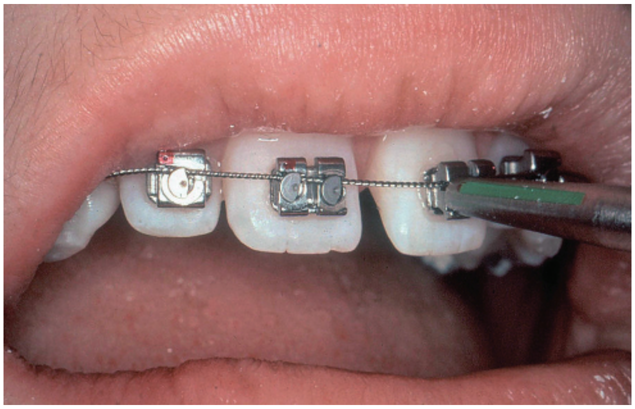


Fig. 1.9 Mobil-lock brackets showing the double cams required to establish sufficient labial slot face on the upper central incisor and the inadequate labial face on the lateral incisor. The 'screwdriver' was hard to use in the buccal segments.

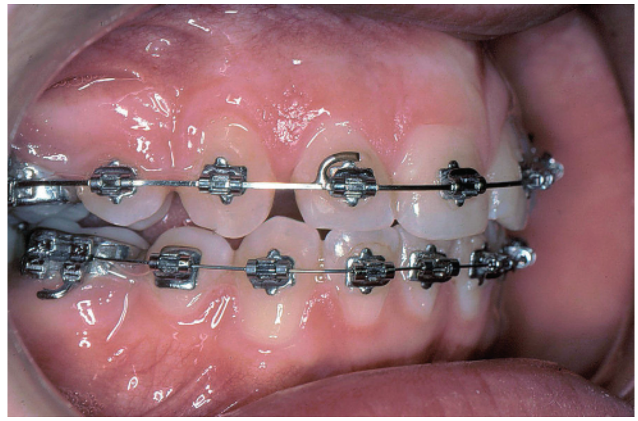


Fig. 1.10 Activa brackets showing the unwanted bracket width, the absence of tie-wings which enforced the elastomeric chain to be placed behind the archwire and the unusual bracket base which was intended to indicate the facial axis of the teeth but contributed to the poor bond strength. The premolar tooth has a later, more conventional bracket base.

Mobil-Lock brackets (Forestadent Bernhard Foerster GmbH, Westliche 151, 75173 Pforzheim, Germany) had a rotating cam which was turned with a 'screwdriver' thus covering part of the labial surface of the slot. The wire could be tightly or loosely engaged by the degree of rotation of the cam. These brackets were well engineered by the standards of the day, but a major limitation was the narrowness of the resulting labial face of the slot. This gave very poor rotational control to the extent that upper incisor brackets were given twin cams to increase the effective bracket width (Fig. 1.9). Another problem was the difficulty of access to open and close premolar brackets with the straight 'screwdriver'.

Activa brackets[32] ('A' company, San Diego, California) had a rotating slide which therefore gave a concave inner radius to the labial surface of the slot. This increased the effective slot depth with small diameter wires, diminishing labio-lingual alignment with such wires. The slide was retained on the mesial and distal ends of the slot and this made for a wider than average bracket which reduced the interbracket span with the consequent disadvantages (Fig. 1.10). The slide was also prone to breakage. The absence of tie wings was an additional nuisance when placing the elastomeric chain and the unfamiliar shape of the early bonding base made bracket positioning more difficult. Finally, a combination of the design features substantially reduced bond strength. In spite of these substantial drawbacks, cases could be successfully treated which demonstrated the now familiar advantages of self-ligation, but the deficiencies of the design ensured that they were only adopted by a minority of enthusiasts.

The Time2 bracket (Adenta GmbH, Gliching, Germany) superficially resembles a SPEED bracket, but unlike the SPEED clip which has a vertical movement, the Time clip rotates into position around the gingival tie wing and rotates towards the occlusal rather than the gingival wall of the slot. Early versions suffered from displacement of the clips and important but subtle changes in clip design were needed to sufficiently reduce this tendency and ensure its continued availability and success. Early production examples of many self-ligating designs have needed significant modification. The negative effect of such initial problems with self-ligating brackets has sometimes hindered subsequent popularity even when the problems have been very largely overcome.

Damon SL brackets[33,34] ('A' Company, San Diego, California) also became available in the mid 1990s and had a slide which wrapped round the labial face of the bracket. These brackets were a definite step forward, but suffered two significant problems – the slides sometimes opened inadvertently due to the play of the slide round the exterior of the bracket and they were prone to breakage due to work-hardening on the angles of the slide during manufacture

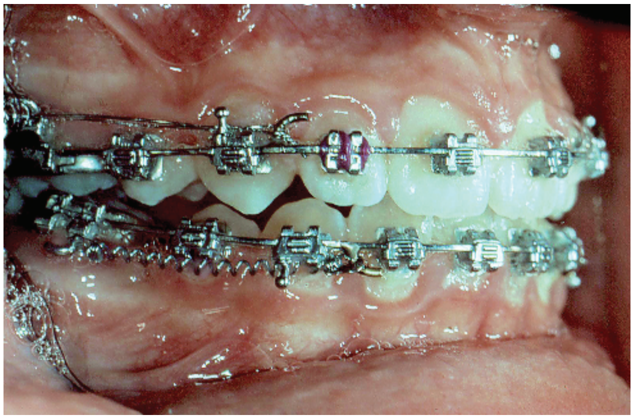


Fig. 1.11 Damon SL brackets showing the previous loss of a slide on the upper lateral incisor. The tie-wings have enabled elastomeric ligation to continue but the potential advantages of self-ligation have been lost on that tooth.

(Fig. 1.11). The study by Harradine (2001)[39], quantified these problems. In 25 consecutive cases in treatment for more than 1 year, 31 slides broke and 11 inadvertently opened between visits. This compared with 15 broken and lost elastomeric ligatures in 25 consecutively treated cases with conventional brackets, so the difference in ligation fragility was not enormous, but when a clinician has paid extra for a novel bracket design and the main design feature is not highly robust and is susceptible to inexpert handling from inexperienced operators, it has a definite negative effect on widespread adoption of that bracket. Nevertheless, these brackets generated a substantial increase in the appreciation of the potential of self-ligation.

Damon2 brackets (Ormco Corporation, 1717 W. Collins Ave., Orange, CA 92867) were introduced to address the imperfections of Damon SL. They retained the same vertical slide action and U-shaped spring to control opening and closing, but placed the slide within the shelter of the tie wings. Combined with the introduction of metal injection molding manufacture, which permits closer tolerances, these developments almost completely eliminated inadvertent slide opening or slide breakage and led to a further acceleration in the use of self-ligation. However, the brackets were not immediately and consistently easy to open and this aspect of functionality is important to the new user. Also, it was possible for the slide to be in a half-open position, hindering archwire removal or placement.

Fig. 1.12 Early Damon3 brackets. The mechanical linkage between the resin and metal components was subsequently strengthened to prevent this separation.

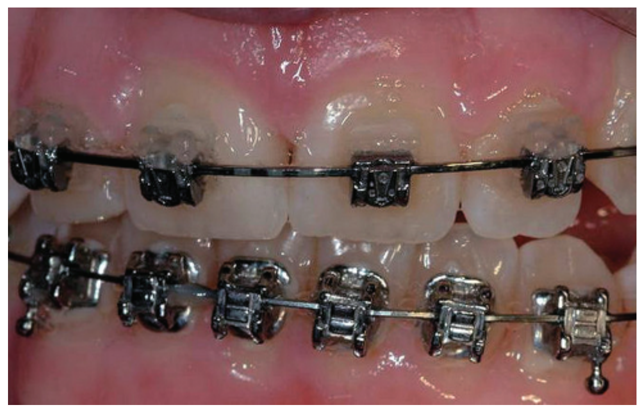
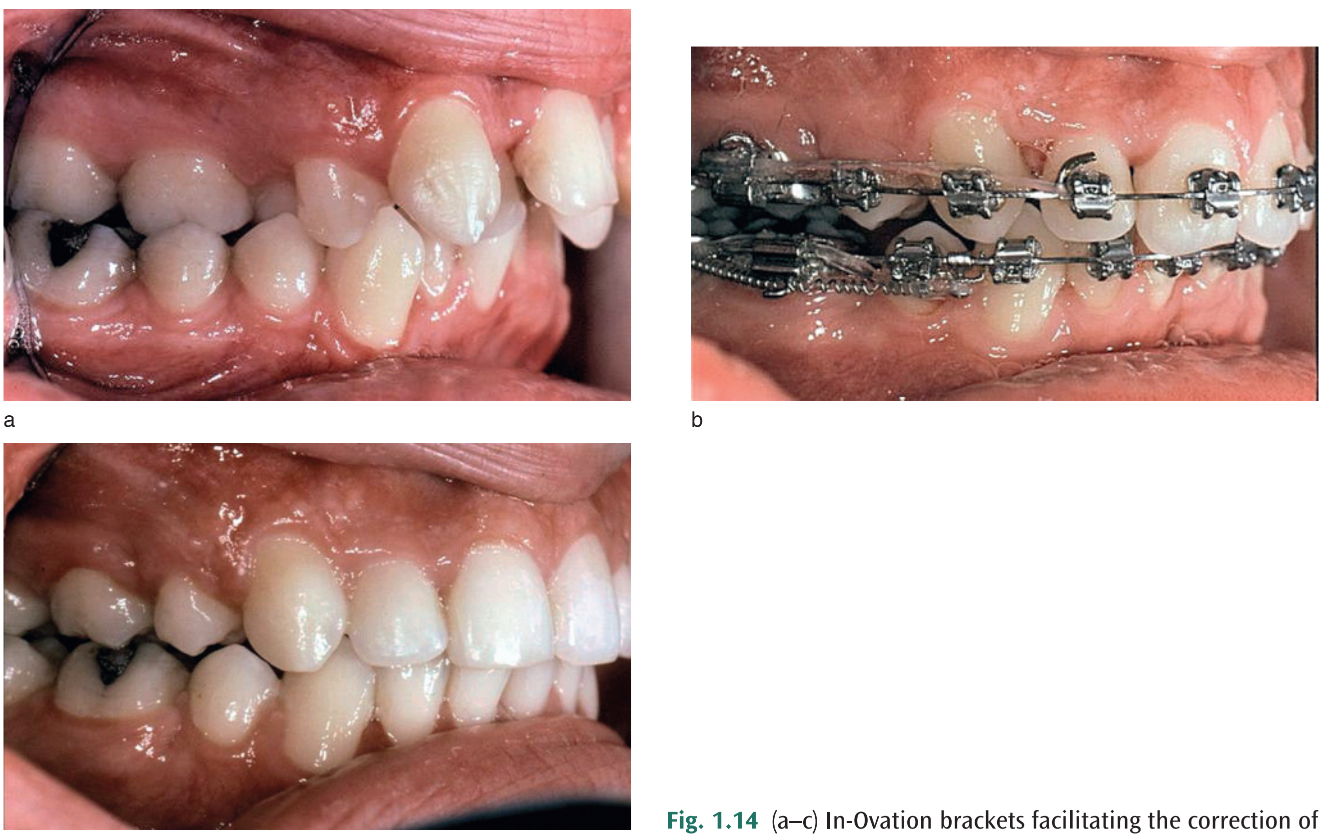


Fig. 1.13 Loss of resin tie-wings from early Damon3 brackets. An additional metal insert corrected this problem which was shown by finite element analysis to arise from repeated indirect occlusal stress.

Damon3 and Damon3 MX brackets (Ormco Corporation, 1717 W. Collins Ave., Orange, CA 92867) have a different location and action of the retaining spring and this has produced a very easy and secure mechanism for opening and closing. In addition, Damon3 brackets are semi-esthetic. However, early Damon3 production brackets suffered three very significant problems: a high rate of bond failure, separation of the metal from the reinforced resin components (Fig. 1.12), and fractured resin tie-wings (Fig. 1.13). These three problems all received fairly rapid and effective investigation and correction, but illustrate that it continues to be a significant challenge for manufacturers to extrapolate from the experience with prototype brackets in the hands of skilled enthusiasts to subsequent full-scale production and the use by relative novices. The more recently launched all-metal Damon D3 MX bracket has clearly benefited from manufacturing and clinical experience with previous Damon brackets. As with other brackets, such as SPEED and In-Ovation (GAC International Inc., 355 Knickerbocker Avenue, Bohemia, NY 11716), it also features a slot for drop-in hooks, mentioned above in the list of ideal requirements.

In-Ovation R were originally called In-Ovation brackets and are very similar to the SPEED bracket in conception and design, but of a twin configuration with tie wings. Both of these additional features probably contributed to a greater acceptability of these brackets to the new user than the long-established SPEED brackets. In 2002, smaller brackets for the anterior teeth became technically possible and available – In-Ovation R (R for reduced, referring to the reduced bracket width) and this narrower width was desirable in terms of greater interbracket span. The bracket subsequently became known as System R before reverting to the name In-Ovation R. They are a successful design (Fig. 1.14), but some relatively minor disadvantages in relation to the list of ideal requirements can be experienced (Fig. 1.15). Some brackets with this type of clip which moves vertically behind the slot are difficult to open and this is more common in the lower arch where the gingival end of the spring clip is difficult to visualize. Excess composite at the gingival aspect of brackets in the lower arch can be difficult to see and may also hinder opening. Similarly, lacebacks, under-ties and elastomerics placed behind the archwire are competing for space with the bracket clip. Interestingly, both SPEED and System R and also the similar and the more recent Quick brackets (Forestadent Bernhard Foerster GmbH, Westliche 151, 75173 Pforzheim, Germany) have aimed to address some aspects of this potential difficulty by providing a labial hole or notch in the clip in which a probe or similar instrument can be inserted to open the clip. The need to acquire the expertise of opening an unfamiliar



a b c

Fig. 1.14 (a–c) In-Ovation brackets facilitating the correction of a severely irregular malocclusion.

Fig. 1.15 In-Ovation R brackets. The small flexible clip is failing to maintain engagement of the archwire.

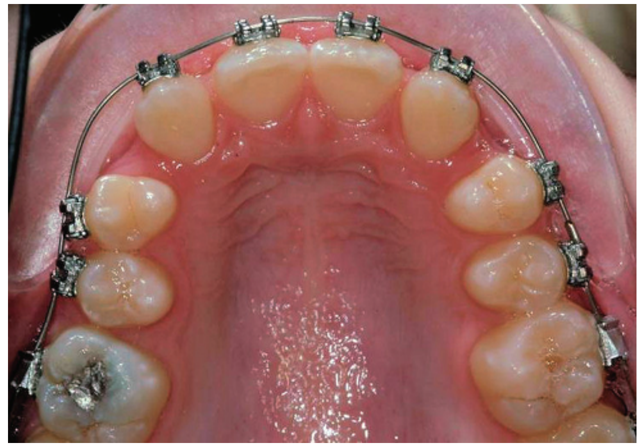


Fig. 1.16 Early SmartClip brackets. The 0.018" nickel–titanium archwire was too uncomfortable for the patient to be engaged in these premolar teeth. The more recently developed spring clip addresses this by being less stiff. The easier archwire insertion has to be balanced with the requirement to keep all appropriate archwires engaged in the slot.

bracket can dishearten the new user of self-ligating brackets and these more recent refinements of the method of opening are a definite advance in this respect. These refinements are also typical of the incremental improvement of self-ligating brackets which can take place without being appreciated by clinicians who have experienced difficulties with earlier production examples.

SmartClip (3M Unitek 3M Center, St Paul, MN 55144–1000) retains the wire by two C-shaped spring clips either side of the bracket slot. The pressure required to insert or remove an archwire is therefore not applied directly to a clip or slide, but to the archwire which in turn applies the force to deflect the clips and thus permit archwire insertion or removal. This mechanism therefore has to cope with providing easy insertion and removal through the jaws of the clips but must also prevent inadvertent loss of ligation for both small, flexible archwires and large, stiff archwires. This is a difficult combination of requirements to balance satisfactorily (Fig. 1.16). Other spring clips such as on SPEED and System R brackets with their vertical action, have a rigid bracket component to assist the spring in resisting a loss of ligation and are opened vertically and independently of archwire placement or removal. It became apparent with wider clinical use that the force required for insertion and removal of thick stainless steel wires from SmartClip brackets was uncomfortably high. A recent modification has addressed this difficulty by lowering the effective stiffness of the spring clips.

These examples all illustrate the difficulties which have been experienced by manufacturers aiming to meet the requirements of an ideal ligation system. The resulting imperfections in bracket design have undoubtedly slowed the adoption of self-ligation systems by clinicians in previous years. Current self-ligation designs have benefited greatly from previous clinical experience and from advances in the available production techniques such as metal-injection molding, laser forming and CADCAM technology.

Aside from the undoubted imperfections of many self-ligating designs, a further factor has possibly hindered the development and adoption of self-ligation. There has been an inherent conservatism amongst orthodontists who have tended to persist with the equipment and ideas given to them during their initial training. There has perhaps been an insufficient appreciation of what low friction, secure archwire engagement and light forces might achieve.

Esthetic self-ligating brackets

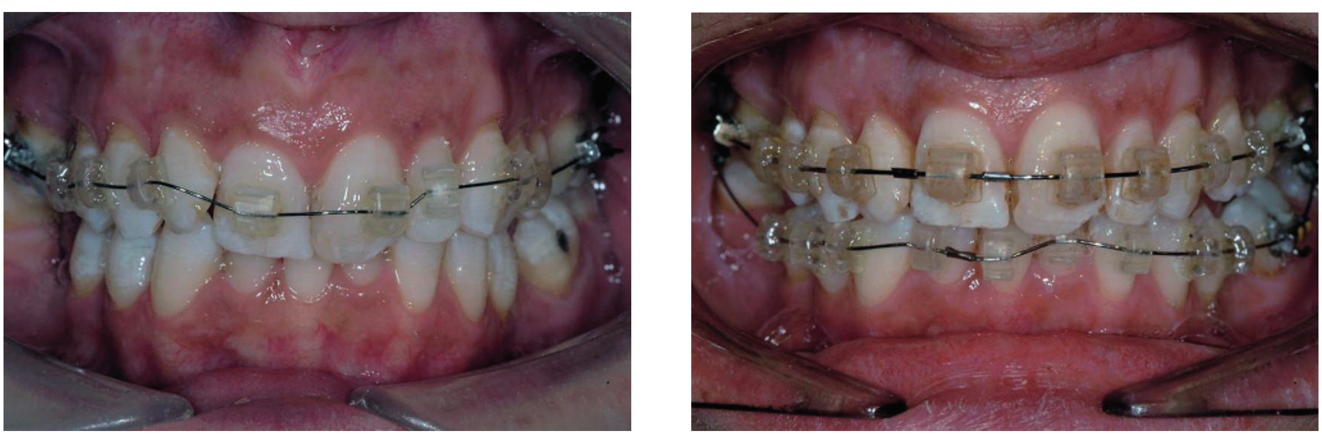
There have been three approaches to production of a more esthetic self-ligating bracket. Firstly, there are lingual self-ligating brackets. There are at least three lingual self-ligating brackets currently available. Forestadent (Bernhard Foerster GmbH, Westliche 151, 75173 Pforzheim, Germany) have their lingual system, sometimes referred to as the Philippe bracket[35]. The ligation mechanism involves deforming two retaining wings – with a Weingart plier to close and a spatula to open. This mechanism requires considerable care not to damage the enamel if an instrument slips and also the wings can be hard to open which can cause detachment of the bracket. Adenta (Adenta GmbH, Gliching, Germany) produce the Evolution bracket which is essentially a lingual version of the Time bracket produced by the same company, whilst the same applies to In-Ovation L from GAC. Ligation is inherently more difficult with lingual appliances, and an easy form of self-ligation clip or slide which can deliver the advantages of security and low friction are equally or even more valuable in that situation where the interbracket spans are inherently smaller. Combining a successful self-ligation mechanism with the particular lingual demands of low profile, easy archwire insertion, inbuilt bite ramps on some teeth and narrow bracket width is a demanding task. Further development is needed on this side of the teeth.

On the labial surface, Oyster (Gestenco Inc., PO Box 240, Gothenburg, Sweden) and OPAL (Ultradent Inc., 505W, 1200S, South Jordan, UT 84095) and Damon3 (partially) are resin brackets whilst Clarity SL (3M Unitek) and In-Ovation C (GAC) have been produced as ceramic brackets with metal clips. The potential limitations of resin polymers as a category of material for orthodontic brackets are well established. Oyster brackets were originally found to be insufficiently robust. Recently they have incorporated a metal hinge with the intention of improving this. OPAL brackets were introduced later and have an ingenious design to address the challenge of the same material being very flexible in one part of the bracket to create a hinge, whilst providing as rigid a bracket slot and as reliable a clip as possible. This is not completely successful, but remains an imaginative use of polymer material. Good results can certainly be achieved, but as with all resin brackets, robustness and longevity are a challenge. Brackets with a semi-transparent labial clip also have to contend with the esthetic problem of food and debris collecting behind the clip where they are relatively inaccessible to oral hygiene measures (Fig. 1.17).

Ceramic brackets are long-established in orthodontics with their known strengths and drawbacks. Clarity SL and IN-Ovation C are likely to combine these properties with those of the corresponding metal self-ligating brackets already discussed. In-Ovation C has a rhodium-coated clip. It is possible that the optimal combination of self-ligation and esthetics will come from a breakthrough in the technology for coating metal brackets.

Active clip or passive slide

This is an issue which has attracted heated debate[26,36] and continues to be stressed by many producers and advocates of particular brackets as a major feature



a b

Fig. 1.17 (a) OPAL brackets on the day of placement in the upper arch. (b) The same patient at the next visit when the lower brackets were placed. The esthetic challenge posed by debris behind the semi-transparent labial clips is apparent.

of importance. Amongst the brackets in Table 1.1 which are currently available, SPEED, In-Ovation R and Quick brackets have a sliding spring clip, which encroaches on the slot from the labial aspect, potentially placing an active force on the archwire. Time2 brackets have a very similar clip, but for closure it rotates round a tie-wing rather than slides into place. These four brackets are all correctly described as having potentially active clips. In contrast, Damon brackets have a slide which opens and closes vertically and creates a passive labial surface to the slot with no intention or ability to encroach upon the slot and store force by deflection of a metal clip. SmartClip, Praxis Glide (Lancer, 253 Pawnee St, San Marcos, California 92069), Carrière LX brackets (Ortho Organisers, 1822 Aston Avenue, Carlsbad, California 92008–7306) and Vision LP (Appendix American Orthodontics, 1714 Cambridge Avenue, Sheboygan, Wisconsin 53081) are also passive systems.

The intended benefit of storing some of the force in the clip as well as in the wire is that in general terms a given wire will have its range of labiolingual action extended and produce more alignment than would a passive slide with the same dimension wire. With thin aligning wires smaller than 0.018" diameter, the potentially active spring clip will be passive and its activity irrelevant unless the tooth (or part of the tooth if it is rotated) is sufficiently lingually placed in relation to a neighboring tooth that the wire touches the inner surface of the clip. In that situation, a higher force will be applied to the lingually placed tooth with an active clip than with a passive slide. An active clip effectively reduces the slot depth from 0.027" (the depth for example of a Damon slot) to approximately 0.018". This shallower slot will potentially place more force for a given archwire which may have adverse consequences, but will provide a longer labio-lingual range of action with small diameter wires. With larger diameter wires, an active clip will place a continuous lingually directed force on the wire even when the wire has gone passive. The difference in labio-lingual range of action will be very small with such intermediate wires, but is one reason why 0.016" × 0.025" or 0.014" × 0.025" nickel titanium wires are recommended as the intermediate aligning wire for the passive Damon system. The paper by Thorstenson and Kusy[18] contains scanning electron micrographs which show very clearly this relationship between small and large wires and active clips and passive slides. It has been suggested that continued lingually directed force on the wire from an active clip will cause additional torque from an undersized wire, but the diagonally directed lingual force may not contribute to any effective third-order interaction between the wire corners and the upper and lower walls of the bracket slot, which is the origin of torquing force. Most types of active self-ligating brackets have therefore more recently addressed this question on upper incisors by extending a section of the upper and lower walls of the slot to act as 'torquing rails'. It is also suggested that a continual lingually directed force may assist with the accuracy of finishing a case, but this has not been demonstrated in the literature or indeed experienced by this author.

Overall advantages or disadvantages of an active clip

It is probable that with an active clip, initial alignment is more complete for a wire of given size to an extent which is potentially clinically useful. It is possible that the difference in effective force levels during alignment is sufficient to significantly change the archform which results from the alignment phase. With modern low modulus wires it is possible to subsequently insert thicker wires into a bracket with a passive slide and arrive at the working archwire size after the same number of visits as with an active clip – i.e. to store all the force in the wire rather than dividing it between wire and clip. The relative stiffness of archwires and the spring clip has not previously been well documented, but a recent study[37] demonstrated both a significant range of spring stiffness for In-Ovation R and SPEED brackets and also – for one bracket type (In-Ovation R) – an average halving of the spring clip stiffness during treatment. This variation and decay in spring force might have substantial biomechanical consequences. Finally, there are the questions of robustness, security of ligation and ease of use. Is a clip which is designed to flex, more prone to breakage or permanent deformation or to inadvertent opening or closing? This question has not been formally investigated. Studies involving the use of different self-ligating brackets in the same patient, or randomly assigned to different patients, are needed to test such hypotheses.

Further advantages claimed for self-ligation

More efficient treatment

Because self-ligation reduces the resistance to tooth movement and provides good security of wire engagement, it is natural to suggest that treatment might be more rapid. Several investigations have examined the hypothesis that self-ligation provides greater treatment efficiency in terms of length of treatment and number of visits, in addition to the reduction in chairside time which has been discussed earlier[13,38]. More rapid treatment with fewer visits would clearly be an advantage from the patients' viewpoint and would also be more cost effective. Currently available self-ligating brackets are more expensive than most good quality tie-wing brackets. A modest balancing factor is the cost of elastic ligatures which are, of course, not required. However, this significant extra cost must be measured against any savings in time, which is an expensive commodity. The wider question is whether self-ligation enables shorter treatment overall.

A study of treatment efficiency by Harradine[39] found the following: a modest average time saving from a reduction in archwire placement/removal of 24 seconds per arch; a mean reduction of 4 months in active treatment time from 23.5 to 19.4 months; a mean reduction of four visits during active treatment from 16 to 12; and the same average reduction in peer assessment rating (PAR) scores for matched cases. These cases were treated in the 1990s with no change in extraction philosophy or treatment goals from concurrent treatment with conventional brackets.

A study by Eberting *et al.*[40] of intrapractitioner differences in three practices found an average reduction in treatment time of 7 months (from 30 to 25) and seven visits (from 28 to 21) for Damon SL cases compared to conventional ligation. In two of the three centres, the American Board of Orthodontics (ABO) irregularity scores were more improved with the Damon SL brackets to a statistically significant extent. These two studies support a view of clinically significant improvements in treatment efficiency with passive self-ligating brackets. The more recent bracket types would be expected to show still better treatment efficiency because they are less prone to breakage or loss of the clips and slides, are easier to open and close, are frequently of more effective slot dimensions and are used with greater understanding of the optimal archwire selection and appointment intervals.

However, not all subsequent studies have found improvements in treatment efficiency. Five random controlled studies which between them compare Damon and Smartclip brackets with conventionally ligated brackets have examined the alignment phase of treatment[25,41–44]. All five failed to find a significant overall increase in the speed of alignment, although Pandis *et al.*[42] found that mild crowding was eliminated more rapidly with Damon2 than with conventional brackets in the hands of the same operator. Another study by Miles[45] found no improvement in the rate of en masse space closure with self-ligating brackets, although at that stage of the treatment, there was no relative movement between the archwire and the self-ligating brackets which were all mesial to the remaining spaces. It seems very probable that self-ligation does not confer a blanket advantage in treatment efficiency and that factors such as treatment interval, archwire sequence, extraction pattern and case mix are significant. Further studies are in progress with a variety of bracket types and this is a rapidly moving field of enquiry. Studies which have followed cases through to completion have yet to appear in print.

Qualitative differences in tooth movement with self-ligation

It would be incomplete when looking at the current situation with self-ligation not to mention some of the hypotheses about qualitative differences which have been put forward and which are currently being investigated. Essentially, these hypotheses reflect a proposal that self-ligation – and particularly passive self-ligation – enables tooth-moving forces to be sufficiently light that forces from the soft tissues can compete and interact with them. It is suggested that these lower forces can, for example, result in: wider arches which may be more esthetic; wider arches which have better periodontal health; wider arches which may be more stable; less incisor proclination for a given amount of crowding; less need for extractions; easier class 2 correction through a 'lip-bumper' effect.

These ideas are based on individual case reports and have generated much debate and subsequent studies. However, none of them has yet been directly investigated to a stage where studies have been published.

Self-ligating brackets have a long history of sporadic development which has culminated in a recent explosive proliferation of bracket types. After many years of existence as a category of orthodontic bracket, they have finally come of age in terms of design, understanding and popularity. The motive for developing these brackets has progressively changed from a predominant desire for faster ligation to a search for a practical means of combining complete security of ligation with much lower friction. They are now sufficiently robust and user-friendly to reliably deliver most of their potential advantages. Whilst the core advantages of self-ligation are now well established, the proposals that self-ligation provides more rapid or qualitatively different treatment results are exciting and important, but are yet to be supported by formal investigations. We still have much to learn about the best use of self-ligation, but these brackets are clearly set to play a major role in orthodontic treatment for the foreseeable future.

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