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Revisiting the Functionally Generated Path Technique: Is this an Aid to Predictable Digital Occlusal Design? Part 1: Introduction and Background

Abstract: Registering a pre-existing occlusal scheme is paramount to the long-term success of a fixed restoration(s) and a requirement when working conformatively, whether in analogue or digital format. Part 1 of this two-part series highlights those occlusal schemes that provide difficulties using established techniques in arriving at a predictable restoration requiring minimal occlusal adjustments chairside. Part 2 introduces the theory of the functionally generated path (FGP) technique, and two cases involving implant-retained restorations will be used to highlight the benefit of adopting this technique into the digital workflow in the provision of occlusally precise restorations.
CPD/Clinical Relevance: This article provides an overview of difficult occlusal schemes and identifies those that would benefit from using the functionally generated path technique in the provision of occlusally correct restorations.
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Occlusion is of key importance in the provision of a long-lasting and functional restoration. Particularly when working conformatively, it is imperative that the correct information is provided to the laboratory to fabricate the appropriate restoration. Therefore, understanding occlusion and the challenges faced when patients do not conform to the ideal Class I occlusal relationship is fundamental to being able to provide a restoration that is predictable and accurate, with minimal occlusal adjustments required chairside at the fit appointment. This information is just as important if working with a digital format as errors can be amplified and may go unnoticed until the final fit. Milled zirconia restorations can generally only undergo a limited degree of adjustment before having to be remade. Part 1 of this two-part series highlights those difficult occlusal cases that would benefit from the use of the functionally generated path (FGP) technique to help avoid some of these errors by providing an accurate and predictable occlusal scheme for the final restoration. Part 2 explains the FGP technique and its adaptation from its analogue background to the digital workflow. Two cases of implant-retained restorations are used to demonstrate the technique step by step.

Jose-Luis Ruiz and Gordon Christensen have 'three golden rules' in their approach to occlusion.[1,2] These 'rules,' outlined below, represent an occlusion in the ideal world, and an occlusion to aim for

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when working in reorganized fashion, but it must be understood that when working conformatively, it may not be possible to achieve all these ideals:

- Bilateral and even occlusal contacts around the arch.
- Posterior tooth disclusion through anterior and canine guidance – namely in mandibular excursions, the anterior teeth remain in contact, with the posterior teeth being out of occlusion. This is also known as a mutually protective occlusion.
- An unobstructed 'envelope of function'.

Mehta and Banerji stated that:

> 'The occlusal scheme is considered to be stable ('mutually protective'), when the patient displays a protrusive mandibular movement, the anterior guidance coupled with the inclination of the condylar path should collectively aim to separate (or disclude) the posterior teeth from each other, thereby avoiding any harmful occlusal contacts which may otherwise culminate in cuspal fractures, repeated restoration fracture, recurrent decementation of indirect restorations, pathological tooth wear or fremitus. This culminates from the fact that the posterior teeth are closest to the fulcrum, ie, the temporomandibular joint (TMJ) where the forces are the highest in a third order lever situation. In the position of maximum intercuspation, only light occlusal contacts should exist between the anterior segments, with occlusal loading primarily taking place between the posterior teeth'.[3]

This leverage is clearly demonstrated in Figure 1b, namely the closer the tooth is to the nutcracker hinge joint, the greater the pressures that are applied for any given applied force. Intra-orally, the closer a single tooth contact is to the TMJ (Figure1a), the greater the leverage and pressures exerted, and therefore the higher the chance of tooth or restoration fracture.

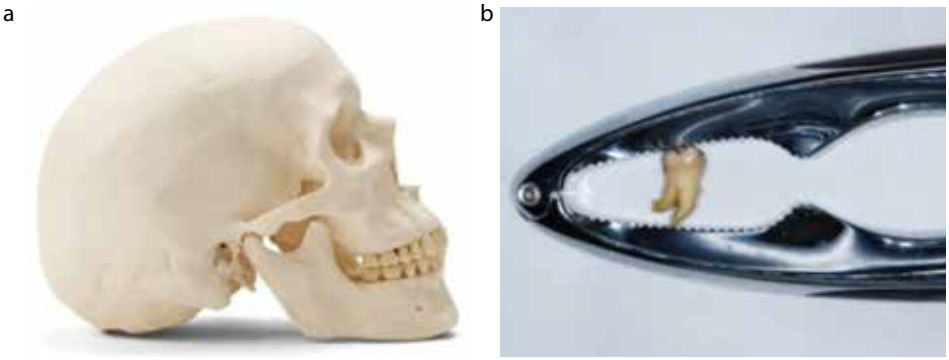

Figure 1. (a) Right lateral view of a skull. **(b)** The principle of a nutcracker and leverage.

Conformative versus reorganized treatment

Providing the correct occlusal shape for the final restoration(s) should ensure that:

- The restoration fits harmoniously into the static occlusion in the intercuspal position (ICP).
- The occlusal scheme in the dynamic excursive mandibular excursions is harmonious with the patient's current guidance, without introducing any interferences posteriorly on the new restoration.

In the provision of indirect restorations, there is a choice between working conformatively or in a reorganized fashion. Working conformatively is generally the easiest and most predictable, but largely restricted to the provision of one or two restorations at a time.[4]

When working conformatively, the technician locates the opposing models together and can easily build the new occlusion into this static intercuspal position. However, unless the models are mounted on a semi- or fully adjustable articulator with facebow recordings, the dynamic occlusion, namely lateral and protrusive mandibular excursions, can only be provided through educated guesswork and appreciating that final occlusal refinements will have to be carried out at the fit appointment.

When working conformatively with a digital workflow, occlusal planning with or without a digital articulator will result in a similarly predictable occlusion to that produced working conventionally in analogue format. Comparing digital methods versus conventional methods, Iwaki *et al* showed significant discrepancies when one quadrant is scanned and more than one tooth is prepared.[5]

Working in reorganized format usually implies that multiple units around the mouth are being provided, often accompanied by changes in the vertical dimension. This type of complex treatment must be carried out on a semi- or fully adjustable articulator and even then, it is challenging for the dental technician to reproduce the full range of mandibular excursions.

In such difficult reorganized occlusal cases, errors can potentially be highlighted further when using computer-aided design and computer-aided manufacturing (CAD-CAM) where the digital articulators available within the software, although in the stage of rapid development, are still in their formative years. Furthermore, in those cases involved with complicated occlusions, forming restorations with occlusally correct morphology is difficult to provide with any degree of predictable accuracy. As this article deals with a technique applicable only when working conformatively, there is little merit in describing the many steps involved in reorganizing an occlusion, whether in analogue or digital format.

Articulators

Analogue

Hinge and free plane articulators: the main disadvantage of these articulators is that they cannot reproduce any mandibular excursions.

Regarding semi-adjustable articulators: although condylar and Bennet angles can be set on many semi-adjustable articulators, as the name implies, they can only go some way to reproducing mandibular excursions. For more predictable accuracy these articulators are not sophisticated enough, particularly for the more complex occlusal schemes encountered. Simpler semi-adjustable articulators that only allow the use of average settings are, correspondingly, less accurate.

Regarding fully adjustable articulators: these come closest to accurately reproducing the full range of mandibular excursions as well as factoring in any side-shift the patient may have. The costs of these articulators and associated orthopantographs (circa £50,000) are too high for most practitioners to purchase, and it can take up to half a day to carry out all the registrations required as the process is extremely complex. When working conformatively to provide a single crown, this articulator is not a viable option.[6]

Digital

A digital articulator is a computer software tool that can simulate the movements of the mouth as per traditional articulators within the computer system being used.[7]

However, when comparing digital methods versus conventional methods, Iwaki *et al* showed if only one quadrant is scanned, significant discrepancies occur if more than one tooth is prepared.[5]

In difficult occlusal cases, for example, lacking anterior guidance, errors can potentially be highlighted further when using CAD-CAM where the digital articulators available within the software are, as mentioned previously, still in their development phase, making occlusally correct restorations difficult to provide with any degree of predictable accuracy. Research has also shown that cross-arch scanning can result in distortion of the occlusion when using digital models unless multiple scans are taken (Figure 2).[5,8]

Ahlholm *et al* confirmed these findings, indicating that conventional impression methods show improved accuracy in comparison to digital techniques when completing full-arch impressions.[9,10]

In addition to this, Park *et al* found, from a study of five intra-oral scanners (Cerec Omnicam, CS3500, iTero, Trios, True Definition), that each scanner had a different acquisition method of buccal interocclusal record scans, interpretations of occlusal surface and error correction algorithms, thus they all yielded different discrepancies.[11] It was also shown that each scanner has different accuracy in reproducing interocclusal relationship deviations ranging from 165 to 395 microns (CS 3500 intra-oral scanner), with Planmeca specifically showing some intra-arch variability. That is not to say that the latest scanners are not more accurate with precision to less than 200 microns.[11]

Limitations of articulators

When working in analogue format, facebow recordings and the use of a high-quality semi- or fully adjustable articulator allows the fabrication of a custom acrylic incisal guidance table to help refine difficult occlusal schemes in the laboratory (Figure 3). However, this guidance table, if using average settings, cannot be relied on to entirely refine the occlusal morphology of the planned new restoration.[12]

Digital occlusal planning is much more difficult in complex cases because the formation of a guidance table is currently not possible. Needless to say, the success of the final occlusal scheme achieved is also based on the level of experience of working with the software.

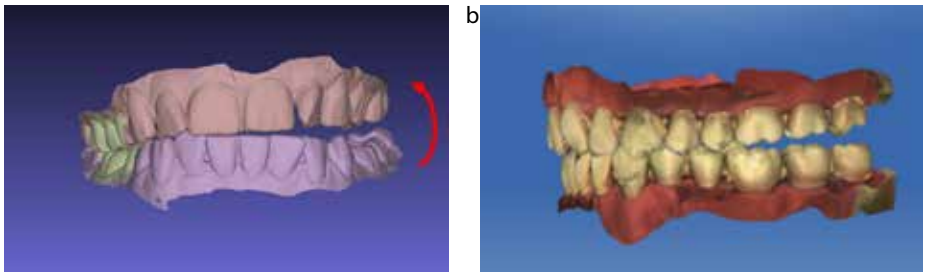

Figure 2. (a, b) Simulation photographs showing a common discrepancy in full-arch scanning. Photographs courtesy of Andrew Keeling (Leeds).

Figure 3. A typical custom acrylic incisal guidance table.

However, in certain clinical situations where, in theory, only one restoration is being planned and a conformative approach seems the simplest way forward, the occlusal schemes and mandibular excursions encountered are so complex and wide that current articulators, whether analogue or digital, cannot necessarily reproduce the wide and unusual intra-oral mandibular excursions with any degree of accuracy to help with occlusal planning. Such situations are outlined below.

Certain severe Class II division 1 occlusions

In these cases, initial guidance is on the posterior teeth before finally providing anterior guidance and posterior disclusion (Figure 4a, b). The forces and pressures generated by the muscles of mastication are such on the last standing teeth that tooth chipping can occur, or, as in this case (Figure 4c), complete vertical fracture of the last standing molar while the patient was asleep and presumably bruxing. The provision of an indirect restoration, such as the gold crown seen in the same patient, is problematic as the restoration must maintain the harmony of the initial posterior guidance and not create interferences that were not there previously.

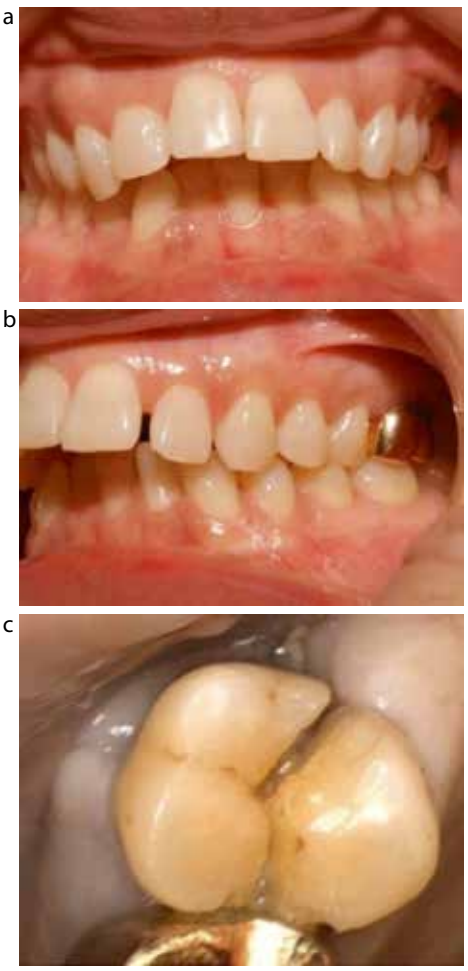

Figure 4. (a) Frontal view in maximum intercuspation. **(b)** Left buccal view including the gold crown, which was placed when the patient was still a teenager as a result of a cusp fracture. **(c)** Occlusal view. The patient fractured the second molar while asleep. It was split vertically and required extraction.

Class III incisal relationship

Jensen stated that:

> 'with Class III jaw relations, patients possess challenging changes in occlusal

Figure 5. Left buccal view. Frequently in Class III cases, many posterior teeth do not meet in ICP: guidance is provided by the posterior teeth.

Figure 6. Frontal view shows a typical Class III malocclusion with only the posterior molars in contact in ICP.

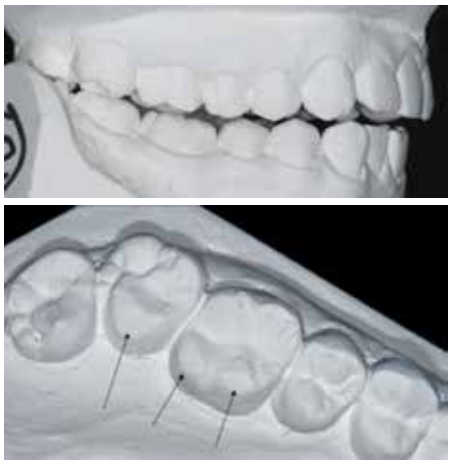

Figure 7. (a) Right buccal view showing an anterior open bite case with no anterior guidance. **(b)** Occlusal view of the upper left molars shows the unusual wear patterns created on the palatal cusps by excursive mandibular movements.

Figure 8. (a) Frontal view showing the teeth in ICP. **(b)** Right buccal view showing the NWS interference in the right molar region on mandibular excursion to the patient's left. Guidance is transferred from the anterior teeth on the left to the posterior teeth on the right. **(c)** Right buccal view of the mounted models showing the large NWS interference on left working side excursion. **(d)** Right buccal view of the patient in left WS with anterior guidance on the lateral incisor and canine re-introduced following extraction of the last standing molar on the lower right and elimination of the NWS interference.

patterns. The interocclusal distance, envelope of motion, chewing stroke, tooth-to-tooth relations, and the determinants of occlusion vary from the criteria established for the Class I or Class II occlusions. The lack of anterior guidance and the added width and length of the mandible have a significant effect on occlusal morphology. Several stable forms of occlusal relationships can be found at one time in the same dentition. The occlusal morphology is dictated by the condylar movements and mandibular size'.[13]

The guidance created by the occlusion in these cases is impossible to predict, particularly as in many cases, a considerable number of posterior teeth are often not in occlusion (Figure 5). Working in analogue fashion is unlikely to allow the creation of the correct occlusal morphology, which is in harmony with the dentition, even if an incisal guidance table is used. If a digital workflow is used, digitally generated occlusions are based on, or at least make reference to, average tooth dimensions and typical morphologies. Unfortunately, there are large standard deviations in these parameters, in part due to differences between males and females and among different ethnic groups within which, concepts such as 'the golden proportion,' have not been found to apply.[14]

Anterior open bites

In severe cases, it is not unusual to find that the only contacts in ICP are either on the last or the last two upper and lower molars on each side. Consequently, guidance in lateral and protrusive mandibular excursions can only be provided by the posterior teeth (Figure 6).

As with the Class III incisal relationship cases mentioned previously, the guidance offered by the posterior teeth is extremely difficult to accurately reproduce using an anterior guidance table unless sophisticated articulators are used. As mentioned earlier these articulators are extremely expensive and time consuming.

The occlusal morphology is dictated by the condylar movements and mandibular size. Figure 7a shows an anterior open bite case mounted in ICP on a semi-adjustable articulator with inter arch contact only on the molars. Figure 7b shows the unusual wear facets created by mandibular excursions over time. When working with a digital workflow, these unusual morphologies that maintain occlusal harmony cannot be accurately predicted. The FGP technique, described in Part 2 of this series, will provide a simple, quick and inexpensive option to capture the required occlusal scheme, whether working in digital or analogue fashion – that is to say the final restoration will be conformative.

The correct occlusal morphology is mandatory in the restorations provided, because forces that produce wear facets in a natural dentition could well result in fractured porcelain if the same contours are not reproduced.[15]

Non-working side interference

Davies *et al* describe this as 'anterior guidance on the back teeth of the non-working side during lateral excursions'.[16]

In the case shown in Figure 8a the patient appears to have normal ICP. However, on a left mandibular working side (WS) excursion,

guidance on that side is rapidly lost as the over-erupted lower right standing molar starts to contact the opposing last standing upper molar creating the non-working side interference (NWS) (Figure 8b). Although this is far from an ideal clinical scenario, if the patient is symptomless, treatment is not necessarily required.

However, in this case, the patient had grade two mobility of the last standing molar on the lower right, and persistent mild-to-moderate pain over a prolonged period in both opposing molars. In Figure 8c, the mounted models clearly show the interference created by the mesial drifting and inclination of the two remaining molars following extraction of the first molar on the lower right many years ago. The patient wanted a resolution to this chronic pain, so the decision was taken to extract the last standing lower unopposed molar – occlusal reshaping was not an option as the degree of tooth reduction required would not leave sufficient viable tooth substance to support a restoration. Figure 8d shows the return to anterior guidance 2 weeks post extraction.

However, when providing posterior restorations, particularly in cases with a shallow overbite, care must be taken to ensure NWS interferences are not introduced with the new restoration. In the case shown in Figure 9, the patient, new to the practice, presented with pain in relation to the upper right second premolar. As part of her history, the patient claimed that the right side had never felt comfortable following provision of two porcelain-fused-to-metal crowns on the lower right first and second molars – a return appointment to her dentist merely reassuring her that the teeth needed time to 'settle'. Instead of settling, the patient's symptoms became worse. Occlusal analysis showed that, as the mandible moved into left working side (LWS), anterior guidance was lost as a result of the painful upper premolar occluding with the over-contoured buccal cusps, which were in a cross-bite with the crown provided on the first molar (Figure 9b). The NWS interference created elicited the patient's symptoms.

A diagnosis of occlusal trauma was made, and the patient allowed reshaping of the buccal cusps to be carried out – medico-legally the patient was warned that there was the possibility of the porcelain fracturing or perforation of the underlying framework during the adjustments and that there was no guarantee that the patient's symptoms would disappear. The adjustments were carried out without mishap, and the patient immediately remarked that her teeth seemed to meet better and she was unable to reproduce the pain. The patient called a few days later to report that all her symptoms had disappeared. Without removing the crown, it is impossible to say whether insufficient buccal cusp height reduction was carried out during preparation forcing the technician to over-contour, or whether the technician inadvertently allowed their artistic licence to create this shape – or indeed a combination of both. The disappearance of the patient's symptoms implies that the diagnosis of occlusal trauma was correct.

This case shows how the introduction of such an interference could well lead, at best, to pain. In other cases, the outcome might have involved porcelain fracture of the crown involved, or if unbreakable materials such as gold or zirconia were to be provided, fracture of the opposing tooth. Either way, this case highlights the importance of providing restorations that conform to the occlusal harmony present, and the consequences if this principle is ignored.

Figure 9. (a) Right buccal view with the teeth in ICP. **(b)** Right buccal view showing the large NWS interference on the last standing restored molars as well as the loss of anterior guidance as the mandible moves into LWS. **(c)** Right buccal view of the patient in LWS following adjustment of the height of the over-contoured buccal cusps on the crown on the opposing first molar, in turn eliminating the NWS interference and re-introducing anterior guidance.

Figure 10. (a) Right buccal view: the patient in ICP. **(b)** Right buccal view showing initial protrusive contact in the edge-to-edge position. **(c)** Right buccal view showing further mandibular excursion in protrusive with crossover and guidance now passing onto the posterior teeth.

Protrusive crossover

This is described by Shillingburg *et al* as 'a protrusive interference that occurs when distal-facing inclines of maxillary posterior teeth contact the mesial-facing inclines of mandibular posterior teeth during a protrusive movement'.[12] In situations where excursions go beyond the incisal edge, the guidance passes from the anterior to the posterior teeth as seen in Figure 10. Provision of crowns in the molar area, which can become involved with guidance in these cases, can lead to discomfort, pain or failure of the restoration or the underlying tooth.[12]

Occlusal anomalies

Cross bites with shallow anterior guidance can lead to the presence of heavy working-side posterior guidance, as seen in this case. The very heavy posterior guidance is more than likely a potential cause of tooth fracture, as seen by the presence of severe cracking of the enamel. Should a crown be required on the last standing molar, it would be preferable not to replicate, or at least minimize, the existing occlusal scheme in Figure 11.

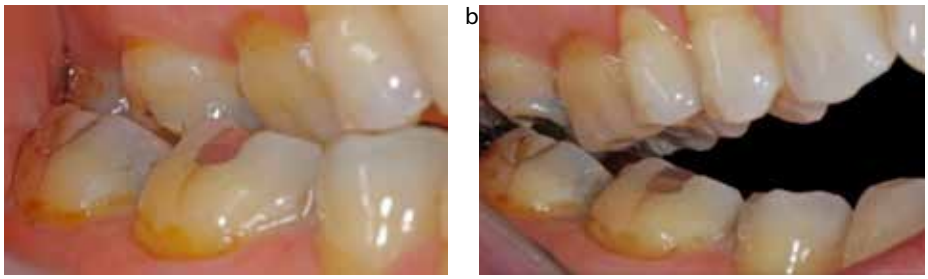

Figure 11. (a) Right buccal view showing the teeth in ICP. **(b)** Right buccal view showing the NWS interferences present as the patient moves into LWS.

Observations

It is clear from the complicated occlusal schemes outlined, that working conformatively in order to maintain the occlusal scheme is extremely difficult and, if incorrect, could well result in the provision of an indirect restoration that may not be in harmony with the patient's mandibular excursions – and these are the very cases where occlusal harmony is paramount. If working with traditional materials, such as gold or porcelain fused to metal, numerous time-consuming adjustments can be made to the restorations without necessarily compromising their structural integrity. The time taken to make these adjustments can be considerable, and the restoration may also require to be returned to the laboratory for reshaping and repolishing/re-glazing prior to the final fit.

However, if working with a digital workflow, the final restoration is, almost certainly, likely to be milled, for example in zirconia. Final adjustments to materials such as milled 3, 4 or 5Y zirconia can then be extremely time consuming, or, worse still, impossible, resulting in an expensive re-make.

The errors often seen are either the restoration being in infra-occlusion or supra-occlusion (that is to say, high in the bite). In addition, the occlusal morphology created can also result in either WS, NWS and/or protrusive interferences. In turn, this highlights the importance of recording and reproducing a bite registration accurately in these extremely difficult cases.

Restorations milled in zirconia in severe infra-occlusion

Milled zirconia restorations in severe infra-occlusion inevitably must be redesigned and remade. However, there is no guarantee of success the second time around as similar problems with occlusal design could well be repeated. The restorations could be altered by the addition of feldspathic porcelain – however, as the milled zirconia restoration was not designed as a coping to provide the recommended support for the addition of porcelain, it risks the chance of delamination in function under loading. The bond of feldspathic porcelain to zirconia is weaker than that achieved with the more conventional porcelain-fused-to-metal restorations, and is generally not recommended as a combination of materials. This weakness is mainly due to an absence of an oxide bond between the feldspathic porcelain and zirconia.[17] Minor corrections to all zirconia restorations, if made, should be carefully carried out using diamond burs or silicone points containing diamond particles as undue force can result in fractures, breakages or micro-cracks from areas of occlusal adjustment.[18,19]

If feldspathic porcelain is to be used over a zirconia core, there should be adequate framework design incorporating proper veneering ceramic support and thickness, as these are factors implicated in the ceramic survival.[8] One should remember that the literature is full of half-truths about the alleged success of veneered zirconia, where serious ceramic delamination from zirconia, which will obviously ruin any 'cosmetic benefits', frequently gets described as a complication rather than as a frank failure.[20] Any adjustments to the original design carried out as an afterthought are likely to be extensive and unlikely to have the ideal shape for supporting these additions.

Milled zirconia restorations in supra-occlusion

As stated previously, major adjustments can be extremely time consuming, even impossible, on occasion. Furthermore, fractography analysis has revealed that the crack propagation seen originates from wear areas and occlusal adjustments.[21–23] Studies have shown that sandblasting and sharp indentations, even at very low loads, are very harmful to the longevity of zirconia.[24–26] Kuraray recommend the following for their product, Katana zirconia block:

> 'corrections should be made carefully, by using a diamond bur or silicone points containing diamond particles. Use a copious spray of water or work on the prosthesis while it is wet. Be careful not to apply undue force, since this may cause a fracture, breakage or micro-cracks from local spot heating'.[19]

It would, therefore, appear prudent to redesign and remake such restorations rather than attempting major reshaping with the resultant risk of failure at some point in the future.

Conclusion

To fabricate a functionally accurate restoration when working conformatively, a clinician needs to be aware of multiple factors when designing restorations for different occlusal schemes. Although the correct occlusal scheme could well be achieved with complex analogue articulators, the additional time involved in making the necessary recordings, as well as the cost involved in the purchase of these articulators, would preclude the use of these techniques in everyday practice. Working digitally, there are limitations as outlined previously, even with the recent advent of newer digital articulators. The cost and complexity of the latest newcomers, such as Modjaw (Villeurbanne, France), are so high and rely on such a high level of operator skill, that anything other than very regular clinical usage would preclude their use in general practice.

Part 2 of this series will describe a method, the analogue FGP technique, and how it can be easily adapted to help generate occlusally accurate restorations digitally, avoiding the use of digital articulators and subsequent possible errors being introduced.

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

Informed Consent: Informed consent was obtained from all individual participants included in the article.

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