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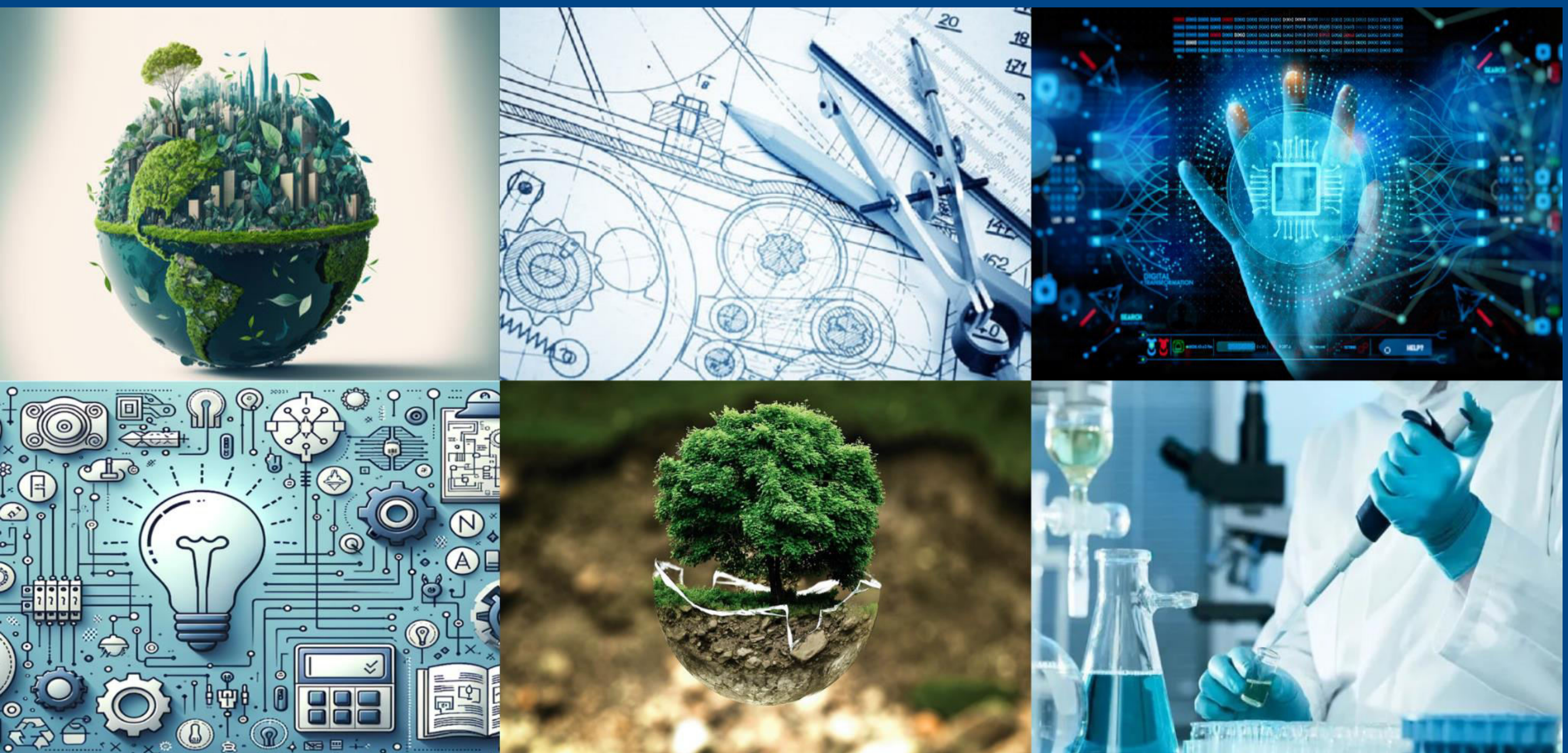

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Compensating Curves in CAD/CAM Dentures- A Narrative Review

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ABSTRACT: For CAD-CAM dentures to be designed with balanced occlusion, stability, and functional efficiency, compensating curves like the Curve of Spee and Curve of Wilson are essential. With the use of CAD software, these curves can be precisely customised according to the jaw connections and occlusal dynamics of each patient. By uniformly distributing occlusal forces and minimising the need for post-insertion corrections through virtual occlusal simulation, compensating curves improve denture retention in CAD-CAM workflows. When compared to traditional methods, advanced manufacturing techniques like milling and 3D printing perfectly mimic these curves, enhancing therapeutic outcomes. But issues like material constraints and the requirement for precise digital records continue to exist. This abstract emphasises how compensatory curves, which are backed by their incorporation into digital design and fabrication processes, are essential for maximising CAD-CAM denture performance.

I. INTRODUCTION

In order to create balanced occlusion and guarantee stability, masticatory efficiency, and patient comfort, prosthodontics uses compensatory curves, which are essential occlusal curvatures integrated into the arrangement of artificial teeth in dental prostheses, such as complete dentures. Complete denture fabrication has grown more accurate and effective with the introduction of computer-aided design and computer-aided manufacturing (CAD/CAM) technologies. Digital processes make it possible to precisely create and replicate compensatory curves, making their implementation into CAD/CAM dentures not only possible but significantly improved. [1]

When combining computer-aided design and computer-aided manufacturing (CAD-CAM) technology to design and fabricate dentures, compensating curves are essential. In removable dentures, especially complete and partial dentures, these curves are crucial for establishing appropriate occlusion, stability, and functioning. [2]
Role of Compensating Curves in CAD-CAM Dentures [3-7]

Establishing Balanced Occlusion:
The anteroposterior (sagittal) and lateral (transverse) curvatures in the occlusal plane of dentures, such as the Curve of Spee and Curve of Wilson, are referred to as compensating curves. In order to replicate natural dentition and provide balanced occlusion during mandibular movements, these curves are implemented. The occlusal surfaces of artificial teeth are aligned by compensatory curves that are digitally modelled in CAD-CAM denture design. This enables opposing teeth to come into synchronous contact during functional movements like chewing or lateral excursions. This improves denture stability and lessens tipping forces. Compared to conventional manual techniques, CAD software allows for accurate customisation of these curves based on patient-specific jaw connections, increasing occlusal harmony.

Enhancing Functional Efficiency:
By directing the mandible into ideal contact locations, well-designed compensatory curves promote effective mastication. This is especially crucial for CAD-CAM dentures since virtual articulators enable precise mandibular movement simulation through digital workflows. The likelihood of discomfort or instability during function is decreased when compensatory curves may be adjusted in CAD software to guarantee that dentures fit the patient's particular occlusal dynamics.

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Improving Denture Stability and Retention:
Particularly in edentulous individuals with resorbed ridges, compensating curves reduce the chance of denture dislodgement by distributing occlusal stresses uniformly throughout the denture base. Digital techniques enable the accurate integration of compensatory curves with maxillomandibular relationship data in CAD-CAM workflows, guaranteeing that the denture base precisely conforms to the underlying tissues, improving stability and retention.

Facilitating Digital Design Precision:
Digital occlusal design modules in CAD-CAM systems allow compensatory curves to be incorporated. These technologies build a virtual model of the patient's oral anatomy using scanned data from intraoral or model scanners, giving doctors the ability to precisely adjust the curves. With compensatory curves customised to the patient's requirements, CAD-CAM guarantees consistent and repeatable outcomes, in contrast to traditional denture manufacture, where manual waxing and trial setups may introduce errors.

Supporting Advanced Manufacturing Techniques:
Compensating curves are converted into the finished prosthesis during CAD-CAM denture manufacture using either additive (3D printing) or subtractive (milling) manufacturing. These technologies' accuracy guarantees that the intended occlusal scheme is maintained by precisely reproducing the planned curves in the denture. For instance, compared to dentures that are treated conventionally, milled denture bases, which are denser and more dimensionally stable, maintain the integrity of compensatory curves and improve clinical results.

Reducing Clinical Adjustments:
CAD-CAM dentures frequently require less post-insertion adjustments since compensatory curves are precisely incorporated during the digital design process. This is due to the fact that the virtual design method ensures appropriate curve alignment by enabling clinicians to simulate and validate occlusal interactions prior to manufacture.

Challenges and Limitations
Learning Curve: Designing compensating curves in CAD software requires expertise in digital dentistry, as improper curve design can lead to occlusal interferences.
Material Limitations: In 3D-printed dentures, polymerization shrinkage of resins may affect the accuracy of compensating curves, potentially compromising the fit and occlusal stability.
Data Dependency: The accuracy of compensating curves relies on precise intraoral scans and maxillomandibular relationship records, which can be challenging in patients with complex anatomies.

Incorporation of Compensating Curves in CAD/CAM Dentures [8,9]
In order to replicate natural occlusal dynamics and guarantee balanced occlusion during mandibular movements (centric, protrusive, and lateral), compensating curves such as the Curve of Spee, Curve of Wilson, Curve of Monson, and Pleasure's Curve (used in monoplane occlusion) are integrated into CAD/CAM dentures. With the use of digital design software and accurate manufacturing processes (such as milling or 3D printing), CAD/CAM technology makes this process easier and offers benefits over traditional approaches.

I. Digital Design of Compensating Curves
Scanning and Model Generation: The process begins with intraoral scanning or scanning of physical impressions/casts to create 3D digital edentulous models. These models serve as the foundation for designing the denture base and tooth arrangement.
Tooth Arrangement in CAD Software: Using CAD software (e.g., 3Shape Dental System, Exocad), clinicians or technicians arrange virtual artificial teeth on the digital models. The software allows precise adjustment of tooth positions to incorporate compensating curves:

Curve of Spee: The mandibular teeth are arranged with a concave anteroposterior curvature, starting from the canine and extending through the buccal cusps of premolars and molars. The maxillary teeth are set with a complementary convex curve.

Curve of Wilson: Mandibular posterior teeth are tilted lingually, with buccal cusps higher, while maxillary teeth are tilted buccally, ensuring working-side contacts during lateral movements.

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Curve of Monson: Teeth are aligned to follow a spherical curvature (8-inch diameter sphere), combining anteroposterior and mediolateral curves for balanced occlusion in all movements.

Pleasure's Curve: In monoplane occlusion, teeth are arranged with a flat or slightly downward-curving occlusal plane, typically using non-anatomic teeth.
Customization: Software tools allow adjustment of the curve's radius, cuspal angulation, and tooth localization to match patient-specific factors, such as condylar guidance (e.g., 30°–40°), incisal guidance, and arch shape. For example, the 3Shape Dental System enables modification of individual tooth positions to align with the occlusal plane and desired curves.

Occlusal Analysis: Virtual articulation simulates mandibular movements, ensuring the curves maintain balanced contacts. Relief areas (e.g., maxillary tuberosity, mandibular mylohyoid ridge) are trimmed digitally to optimize fit and function.

Advantages:
Precise control over curve geometry, reducing manual errors associated with conventional wax setups. Digital archiving allows replication of curves if dentures are lost or damaged. Virtual try-ins (e.g., 3D-printed trial dentures) validate curve placement before final fabrication.

II. FABRICATION OF COMPENSATING CURVES [2,5]

Milling:
The data is sent to CAM software (like WIELAND V2.0.049) for control of milling machines (like WIELAND ZENOTEC T1) after the virtual denture has been designed. Composite blocks or prepolymerized acrylic resin are used to mill the denture foundation and teeth. Accurate curve geometry is ensured by the milling process, which accurately reproduces the intended compensating curves with deviations as small as 0.50 mm for occlusal surfaces. Because there is no polymerisation shrinkage and the curves are maintained, milled dentures provide better fit and retention.

3D Printing:
As an alternative, trial or final dentures are made using additive manufacturing, or 3D printing. Denture bases and teeth with the intended curves are produced using printers (such as NextDent Denture 3D+). Even while 3D-printed dentures might not be as precise as milled dentures (trueness range: 0.058–0.29 mm), they are nonetheless reasonably priced and can be used for try-ins to confirm curve placement. Prefabricated artificial teeth are bonded to milled or 3D-printed bases to preserve the curves in the finished prosthesis.
Advantages:
Unlike traditional heat-polymerized dentures, milling preserves curve accuracy by removing shrinkage. Before final production, trial dentures can be quickly prototyped using 3D printing to test curve functionality. Because curves are digitally pre-validated, both approaches minimise chairside modifications.

III. CLINICAL WORKFLOW AND VALIDATION [4,10]

Workflow:
Impressions and Records: Conventional impressions or intraoral scans capture the edentulous ridges and maxillomandibular relationship (MMR). Occlusion rims (often 3D-printed) establish the occlusal vertical dimension (OVD) and MMR.
Trial Dentures: Many CAD/CAM systems (e.g., AvaDent, 3Shape) incorporate a try-in phase using 3D-printed trial dentures to evaluate aesthetics, phonetics, and occlusal balance. The compensating curves are assessed for protrusive and lateral contacts.
Final Fabrication: After adjustments, the final denture is milled or printed, with teeth bonded to the base. The curves are preserved in the final prosthesis, ensuring functional occlusion.
Validation:
Digital articulation in CAD software simulates condylar and incisal guidance, ensuring the curves align with patient-specific mandibular movements.
Clinical try-ins confirm the curves' effectiveness, with fewer adjustments needed compared to conventional dentures due to CAD/CAM precision.
Post-insertion evaluations (average 2.7 appointments) assess occlusal harmony and patient satisfaction.

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IV. SPECIFIC CONSIDERATIONS FOR COMPENSATING CURVES IN CAD/CAM DENTURES [11,12]

Curve of Spee:
Incorporated by aligning mandibular buccal cusps in a concave arc and maxillary cusps in a convex arc. Digital tools adjust the curve's radius (e.g., 4 inches) based on condylar guidance, ensuring protrusive balance. Example: In a CAD/CAM denture, the mandibular first molar's buccal cusp is set 1–2 mm higher than the second premolar's, forming a concave curve.

Curve of Wilson:
Achieved by tilting mandibular posterior teeth lingually and maxillary teeth buccally. CAD software ensures precise angulation (e.g., 5°–10°) for lateral balance. Example: The mandibular first premolar's buccal cusp is tilted lingually to contact the maxillary premolar during lateral excursions.

Curve of Monson:
Designed as a spherical curvature, aligning all cusps to an 8-inch diameter sphere. Digital templates (e.g., Broadrick flag equivalent in 3Shape) guide the arrangement. Example: All mandibular teeth are set to touch a virtual spherical surface, ensuring balance in all movements.

Pleasure's Curve:
Used in monoplane occlusion setups, with flat or slightly downward-curving occlusal planes. Non-anatomic teeth are arranged digitally to minimize lateral forces. Example: Mandibular premolars and molars are set flat, with a 0.5 mm downward tilt anteriorly, for patients with resorbed ridges.

V. ADVANTAGES OF INCORPORATING COMPENSATING CURVES IN CAD/CAM DENTURES [13]

Precision: Digital design ensures accurate curve geometry, with deviations as low as 0.50 mm for occlusal surfaces, compared to manual wax setups.
Efficiency: Reduced chairside time and fewer appointments (average 4.1 visits vs. 5 for conventional dentures) due to pre-validated curves.
Retention and Fit: Milled CAD/CAM dentures eliminate polymerization shrinkage, preserving curve integrity and improving retention.
Digital Archiving: Curves are stored digitally, allowing replication if dentures are lost, a significant advantage for older adults.
Customization: Software allows tailoring curves to patient-specific anatomy (e.g., steep condylar paths require steeper Curve of Spee), enhancing occlusal balance.

VI. CHALLENGES AND LIMITATIONS [14,15]

Learning Curve: Clinicians and technicians require training to master CAD software for precise curve design.
Cost: Initial investment in CAD/CAM systems (software, scanners, milling machines) is high, though long-term costs are lower.
3D Printing Limitations: 3D-printed dentures may have lower shear bond strength for relining, potentially affecting curve stability over time.
Clinical Validation: While digital try-ins reduce adjustments, some studies note the need for additional visits to optimize aesthetics and vertical dimension, which may affect curve placement.
Research Gaps: Limited studies specifically address compensating curves in CAD/CAM dentures, with most focusing on fit, retention, and material properties.

VII. RECENT STUDIES AND EVIDENCE [16-19]

Using the 3Shape Dental System, a 2017 study showed that CAD/CAM dentures were feasible with precisely milled compensatory curves that were digitally generated (0.50 mm occlusal deviation). According to a 2021 systematic review, CAD/CAM dentures provide accurate inclusion of compensating curves and give superior mechanical properties and trueness of fit (0.058–0.29 mm). According to a 2023 assessment, CAD/CAM dentures enhance retention and cut down on sessions (mean of 4.1 visits), allowing for

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precise curve insertion through digital workflows. The precision of digitally created curves was supported by a 2024 study on 3D-printed CAD/CAM dentures, which verified the placement of prosthetic teeth.

VIII. CONCLUSION

For dental prostheses, such as complete dentures and fixed restorations, to achieve balanced occlusion, compensating curves—such as the Curve of Spee, Curve of Wilson, Curve of Monson, and Pleasure's Curve—are crucial in prosthodontics. These purposefully created curvatures ensure simultaneous tooth contact during centric, protrusive, and lateral mandibular movements by imitating or adapting natural occlusal dynamics. Compensating curves are essential for effective and long-lasting prosthetic results because they reduce residual ridge resorption while improving denture stability, masticatory efficiency, and patient comfort. Digital workflows make it possible to precisely include these curves into CAD/CAM dentures, providing increased precision, reproducibility, and efficiency over traditional techniques. The use of compensatory curves in contemporary prosthodontics, backed by cutting-edge technology and biomechanical principles, highlights their critical importance in maximising occlusal harmony and clinical success despite obstacles like cost and technical expertise.

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