UNIVERSIDAD DE SALAMANCA
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Evaluation of surface roughness height parameters in acrylic resins for prosthetic bases

Evaluación de parámetros de altura de rugosidad superficial en resinas acrílicas para bases protéticas

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Tesis doctoral
Presentada por **Margarida Martins Quezada** para optar
al título de Doctor Internacional en Odontologia por la Universidad de Salamanca

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2024

To my parents,

For instilling in me the restless dreamer’s spirit.

For giving me wings to explore the world.

For nurturing a heart in me that is meant to give.

You have all my embrace and love.

To my supervisor, Prof. Dr. Javier Montero, for graciously welcoming me to the renowned University of Salamanca. I extend my heartfelt gratitude for the opportunity.

To my esteemed advisors, Prof. Dr. André Correia and Prof. Dra. Patrícia Fonseca, who exemplify ethics and professional rigor. I express my sincere gratitude for the elevated standards and challenges placed on me from the very beginning.

To the Department of Mechanical Engineering at the Faculty of Engineering of the University of Porto (FEUP), especially to Prof. Dr. Carlos Fernandes, for his continuous support in the development and application of precision hardware and software for dental materials.

To those who turned words into comfort, my deepest gratitude.

To my family, for imparting integrity, education and values that have shaped me.

To my grandparents, Maria Ana e Manuel Joaquim, for being the timeless love story in my life.

To my guiding stars, Maria José and Alfredo, my godmother and godfather, for illuminating my path and guiding me towards honouring all the promises made to you.

To my parents, I wish to live forever in the sparkle of your eyes and may your hearts always be the home where I belong.

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III. INITIALISMS AND ACRONYMS

ADA – American Dental Association

ADC – Analog to Digital Converter

ANSI – American National Standards Institute

CAD/CAM - Computer-aided design/Computer-aided manufacturing

CNC – Computer Numerical Control

CPT – Control Polishing Tool

FEUP - Faculty of Engineering of the University of Porto Institute of Science

INEGI - Innovation in Mechanical and Industrial Engineering

ISO - International Organization for Standardization

IUPAC – International Union of Pure and Applied Chemistry

MMA – Methyl methacrylate

PMMA – Poly (methyl methacrylate)

SEM – Scanning electron microscope

STL - Standard Tessellation Language

UDMA - Urethane dimethacrylate

IV. ABSTRACT

Background

Poly (methyl methacrylate) (PMMA) is a high versatile polymer extensively used in dental laboratories for various applications. PMMA-based acrylic resins are particularly valued for their ability to provide natural-looking and durable solution for dental patients. Their widespread use is attributed to their low density, ease of manufacturing, favourable mechanical and aesthetic properties, affordability, and minimal toxicity.

The effectiveness of prosthodontic rehabilitations heavily depends on biofunctionality, necessitating the use of materials that are biocompatible with the surrounding tissues and capable of adapting to the complex environment of the oral cavity. PMMA is used for prosthetic bases due to its biocompatibility, helping to avoid irritation, toxicity, and mutagenicity in oral tissues. However, despite these advantages, PMMA does have certain mechanical and physical limitations that make it less than ideal in some aspects.

To mitigate these shortcomings, CAD/CAM (Computer-aided design/Computer-aided manufacturing) technologies are increasingly implemented in dental practices to produce removable prostheses. This technology streamline clinical procedures, improve the accuracy of replication, enhance dimensional precision, and refine surface properties. CAD/CAM is particularly effective in addressing issues associated with porous surfaces and limited durability characteristic of conventional manufactured dentures.

Surface roughness is a significant clinical consideration because it influences the retention of microbial plaque on dental materials, which can lead to increased surface fatigue and reduced biocompatibility. This property is primarily affected by the inherent characteristics of denture base materials, the polishing techniques applied, and the operator's skill. Identifying the most appropriate and relevant roughness parameters to

monitor the desired surface properties remains a challenge. The urgency of determining a set of parameters that effectively correlate with surface functionality has been emphasized.

Objectives

The specific objectives of this thesis were: (1) to validate a new approach for the analysis of surface roughness height parameters; (2) to understand the influence of acrylic resin processing techniques based on the surface roughness height parameters; (2.1) to understand the differences produced in the surface roughness height parameters between conventional and CAD/CAM processing techniques of acrylic resins; (2.2) to understand the proper selection of polishing protocols based on the surface condition immediately after processing; (3) to understand the influence of acrylic resins polishing protocols on the surface roughness height parameters; (3.1) to evaluate the feasibility of a mechanized tool in terms of standardizing the polishing protocol.

Methods

Thirty samples of acrylic resin were produced using five different processing techniques: heat-cured, self-cured, injected-molded, 3D CAD/CAM printed and CAD/CAM milled. These samples were organized into six groups: a control group that included one sample of each type of resin, and five study groups, each containing one sample of each type of resin. Each sample was subjected to the same polishing protocol, which was applied using two different techniques: one conventional and one mechanized (control polishing tool protocol - CPT), with each technique applied to one side of the sample. The present research involved two distinct parts. First, considering the group of 3D printed acrylic resins, a proof of concept was conducted to validate a different approach for analysing surface roughness height parameters: Ra (arithmetic mean roughness), Pa (arithmetic mean height), skewness (Rsk/Psk), and kurtosis (Rku/Pku). Secondly, the surface roughness determinants (inherent characteristics of the denture base materials and polishing protocols) were subjects of analysis. The control group was examined to extrapolate the profilometric measurements (Pa, Psk, Pku) of the specimens directly resulting from the processing techniques. The study group analysed the influence of the polishing protocols on the surface height parameters. The surface roughness measurement was conducted using a contact profilometer. The data obtained were subjected to statistical analysis using the SPSS® program with a significance level set at 0.05.

Results

In the analysis of surface roughness parameters, both Ra and Pa values demonstrated notable differences among the polishing techniques evaluated. ANOVA indicated significant differences ($F = 90.139$, $p < 0.001$), however, the Games-Howell test could not identify significant post-hoc differences due to lack of variance homogeneity. For Ra, ANOVA results ($F = 53.028$, $p < 0.001$) and subsequent post-hoc analysis highlighted significant differences among groups. The analysis of skewness and kurtosis values revealed distinct distribution characteristics among the three polishing techniques.

The analysis of average roughness (Pa) indicated that the conventional polishing technique resulted in significantly higher Pa values compared to the CAD/CAM technique ($t = 4.595$, $p < 0.001$). Heat-cured resins had the highest Pa ($F = 6.976$, $p = 0.06$). Both heat-cured and milled resins exhibited lower coefficients of variation (CV), suggesting more consistent surface finishes. Surface profiles evidenced distinct skewness and kurtosis patterns, highlighting the inherent characteristics of each processing method. The Pa values obtained from both mechanized and conventional polishing techniques were significantly lower than those in the control group. However, mechanized polishing produced notably higher roughness levels compared to the control. Across different resin types, skewness remained relatively consistent and kurtosis values ranged low to moderate. There were no significant differences in the dispersion and pattern of Pa values between polishing techniques.

Conclusions

Surface roughness is a critical clinical factor because it influences the retention of microbial plaque on tissues in contact with denture base resins. This research emphasizes the importance of incorporating the primary profile (P) in surface analysis. The primary profile is crucial to evaluate surface roughness as it represents detailed surface characteristics, including peaks, valleys and all variations in height. Furthermore, specific height parameters like skewness (Psk) and kurtosis (Pku) are important for differentiate surfaces with varying shapes that may present identical Pa values, thereby providing deeper insights into the height distribution across the surface.

In our research, CAD/CAM resins showed lower surface roughness values (Pa), whereas heat-cured resins demonstrated superior consistency in their surface profiles. Intrinsic factors such as polymerization temperature, pressure and composition of poly (methyl methacrylate) (PMMA) significantly affect surface topography and dictate the choice of polishing procedure.

Polishing protocols significantly influence the surface roughness of denture base materials by systematically removing rough layers from the surface. Both mechanized and conventional polishing techniques affect surface topography of acrylic resins. The mechanized protocol consistency delivers uniform skewness and kurtosis values, while conventional method exhibits notable variability in Pa values obtained.

V. RESUMEN

Antecedentes

El polimetacrilato de metilo (PMMA) es un polímero de alta versatilidad ampliamente utilizado en laboratorios dentales para diversas aplicaciones. Las resinas acrílicas basadas en PMMA son especialmente valoradas por su capacidad para proporcionar una solución duradera y de apariencia natural para los pacientes dentales. Su uso generalizado se debe a su baja densidad, facilidad de fabricación, propiedades mecánicas y estéticas favorables, asequibilidad y baja toxicidad.

La efectividad de las rehabilitaciones prostodónticas depende en gran medida de la biofuncionalidad, lo que requiere el uso de materiales biocompatibles con los tejidos circundantes y capaces de adaptarse al complejo entorno de la cavidad oral. El PMMA se utiliza en bases protésicas debido a su biocompatibilidad, ayudando a evitar la irritación, la toxicidad y la mutagenicidad en los tejidos orales. Sin embargo, a pesar de estas ventajas, el PMMA presenta ciertas limitaciones mecánicas y físicas que lo hacen menos ideal en algunos aspectos.

Para mitigar estas deficiencias, las tecnologías CAD/CAM (Diseño Asistido por Computadora/Manufactura Asistida por Computadora) se implementan cada vez más en las prácticas dentales para la producción de prótesis removibles. Esta tecnología agiliza los procedimientos clínicos, mejora la precisión de la replicación, optimiza la precisión dimensional y perfecciona las propiedades de la superficie. El CAD/CAM es particularmente efectivo para abordar problemas asociados con superficies porosas y la durabilidad limitada característica de las dentaduras fabricadas de manera convencional.

La rugosidad superficial es una consideración clínica significativa porque influye en la retención de placa microbiana en los materiales dentales, lo que puede llevar a una mayor

fatiga superficial y reducir la biocompatibilidad. Esta propiedad está principalmente influenciada por las características inherentes de los materiales de base de la dentadura, las técnicas de pulido aplicadas y la destreza del operador. Identificar los parámetros de rugosidad más apropiados y pertinentes para monitorear las propiedades superficiales deseadas sigue siendo un desafío. Se ha enfatizado la urgencia de determinar un conjunto de parámetros que se correlacionen eficazmente con la funcionalidad de la superficie.

Objetivos

Los objetivos específicos de esta tesis fueron los siguientes: (1) validar un nuevo enfoque para el análisis de los parámetros de altura de la rugosidad superficial; (2) entender la influencia de las técnicas de procesamiento de resina acrílica basadas en los parámetros de altura de la rugosidad superficial; (2.1.) comprender las diferencias en los parámetros de altura de la rugosidad superficial entre las técnicas de procesamiento convencionales y las técnicas de procesamiento CAD/CAM de resinas acrílicas; (2.2.) analizar la adecuada selección de protocolos de pulido basados en el estado de la superficie inmediatamente después del procesamiento; (3) estudiar la influencia de los protocolos de pulido de las resinas acrílicas sobre los parámetros de altura de la rugosidad superficial y (3.1.) evaluar la viabilidad de una herramienta mecanizada en términos de estandarización del protocolo de pulido.

Métodos

Se produjeron treinta muestras de resina acrílica utilizando cinco técnicas de procesamiento diferentes: curado por calor, curado en frío, moldeado por inyección, impreso en 3D con CAD/CAM y fresado con CAD/CAM. Estas muestras se organizaron en seis grupos: un grupo de control que incluyó una muestra de cada tipo de resina, y cinco grupos de estudio, cada uno conteniendo una muestra de cada tipo de resina. Cada muestra fue sometida al mismo protocolo de pulido, que se aplicó utilizando dos técnicas diferentes: una convencional y una mecanizada (protocolo de herramienta de pulido de control - CPT), aplicando cada técnica a un lado de la muestra. La presente investigación se dividió en dos partes distintas. Primero, considerando el grupo de resinas acrílicas impresas en 3D, se realizó una prueba de concepto para validar un enfoque diferente para analizar los parámetros de altura de rugosidad superficial: Ra (rugosidad media aritmética), Pa (perfil medio aritmético), asimetría (Rsk/Psk) y curtosis (Rku/Pku). En segundo lugar, se analizaron los determinantes de la rugosidad superficial (características inherentes de los materiales de base de dentadura y protocolos de pulido). El grupo de control se examinó para extrapolar las mediciones profilométricas (Pa, Psk, Pku) de las muestras directamente resultantes de las técnicas de procesamiento. El grupo de estudio analizó la influencia de los protocolos de pulido en los parámetros de altura superficial. La medición de la rugosidad superficial se realizó utilizando un perfilómetro de contacto. Los datos obtenidos fueron sometidos a análisis estadístico utilizando el programa SPSS® con un nivel de significancia establecido en 0.05

Resultados

En el análisis de los parámetros de rugosidad superficial, tanto los valores de Ra como de Pa demostraron diferencias notables entre las técnicas de pulido evaluadas. El ANOVA indicó diferencias significativas ($F = 90.139$, $p < 0.001$); sin embargo, la prueba de Games-Howell no pudo identificar diferencias post hoc significativas debido a la falta de homogeneidad de la varianza. Para Ra, los resultados del ANOVA ($F = 53.028$, $p < 0.001$) y el análisis post hoc posterior destacaron diferencias significativas entre los grupos. El análisis de los valores de asimetría (skewness) y curtosis reveló características de distribución distintas entre las tres técnicas de pulido.

El análisis de la rugosidad promedio (Pa) indicó que la técnica de pulido convencional resultó en valores de Pa significativamente más altos en comparación con la técnica

CAD/CAM ($t = 4.595$, $p < 0.001$). Las resinas curadas por calor presentaron los valores más altos de Pa ($F = 6.976$, $p = 0.06$). Tanto las resinas curadas por calor como las mecanizadas mostraron coeficientes de variación (CV) más bajos, lo que sugiere acabados superficiales más consistentes. Los perfiles de superficie evidenciaron patrones distintos de asimetría y curtosis, destacando las características inherentes de cada método de procesamiento.

Los valores de Pa obtenidos mediante las técnicas de pulido mecanizado y convencional fueron significativamente más bajos que los del grupo de control. Sin embargo, el pulido mecanizado produjo niveles de rugosidad notablemente más altos en comparación con el control. Entre los diferentes tipos de resinas, la asimetría se mantuvo relativamente constante y los valores de curtosis oscilaron entre bajos y moderados. No se detectaron diferencias significativas en la dispersión y el patrón de los valores de Pa entre las técnicas de pulido.

Conclusiones

La rugosidad de la superficie es un parámetro clínico crucial porque impacta directa o indirectamente en la acumulación de placa microbiana en los tejidos que están en contacto con los materiales dentales. Esta investigación subraya la necesidad de integrar el perfil primario (P) en el análisis de la superficie. El perfil primario es esencial para evaluar la rugosidad de la superficie, ya que representa las características detalladas de la superficie, incluidos picos, valles y todas las variaciones de altura. Además, parámetros específicos de altura como la asimetría (Psk) y la curtosis (Pku) son importantes para diferenciar superficies con formas variadas que pueden compartir valores idénticos de Pa, proporcionando así una comprensión más profunda de la distribución de las alturas en la superficie.

En esta investigación, las resinas CAD/CAM mostraron valores más bajos de rugosidad superficial (Pa), mientras que las resinas termopolimerizables demostraron una consistencia superior en sus perfiles de superficie. Como se discutió anteriormente, factores intrínsecos como la temperatura de polimerización, la presión y la composición del polimetilmetacrilato (PMMA) afectan significativamente la topografía de la superficie y dictan la elección del procedimiento de pulido.

Seleccionar la técnica de pulido adecuada es esencial para mejorar el atractivo estético, minimizar la retención de placa bacteriana y aumentar la resistencia a los fluidos orales. Los protocolos de pulido influyen significativamente en la rugosidad de la superficie de los materiales de base de prótesis al eliminar sistemáticamente las capas rugosas de la superficie. Tanto las técnicas de pulido mecanizadas como las convencionales afectan la topografía superficial de las resinas acrílicas. El protocolo mecanizado proporciona consistentemente valores uniformes de asimetría y curtosis, mientras que el método convencional muestra una variabilidad notable en los valores de Pa obtenidos.

1. INTRODUCTION

In historical context, the manufacture of medical devices to replace missing teeth traces its origins to the 6th century BC, marking one of the earliest references to dental prosthetics. Humans developed techniques and used various materials to manufacture devices that replaced missing tooth based on the use of non-metallic materials, such as wood, ivory, or even human teeth (Figure 1) (1, 2).

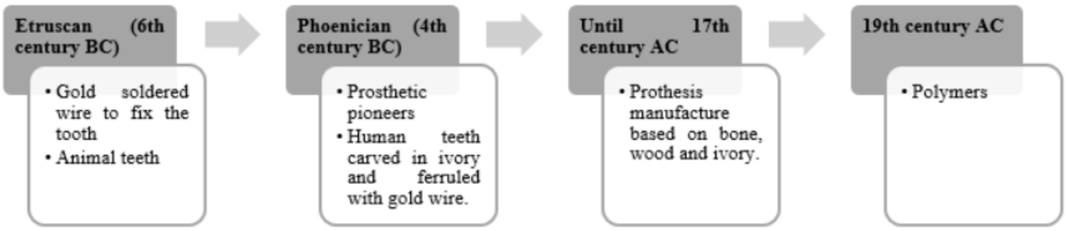


Figure 1. *Evolution of the materials used to manufacture prosthesis until 17th century*

By the mid-19th century, polymers revolutionized the materials used in prosthetic rehabilitation (1, 2). Polymers constitute materials with various applications in dentistry because its recognized properties that cannot be achieved by other materials (2). The main application of polymers occurs in oral rehabilitation, particularly in interim restorations (e.g. crowns) and dental prosthesis (e.g. manufacture of teeth and prosthetic base) (3, 4).

Chemically, a polymer consists of molecules composed of multiple units known as monomers. These units determine the name of the polymer. The process by which monomers unite to form a polymer is termed polymerization reaction. Various factors influence the properties of polymers, including chemical composition, chain polymerization degree, and the presence of branches and bonds between chains (4).

Redtenbacher (2) initially described the polymer poly (methyl methacrylate) (PMMA) in 1843. Since 1940, PMMA has been recognized as a fundamental biomaterial in medical and dental laboratories and clinics. During the second half of the 20th century, PMMA gained considerable popularity. In addition to replacing all alternative materials for the manufacture of prosthetic bases, it demonstrated remarkable results in the production of maxillofacial prostheses, crowns and interim restorations (5, 6).

1.1. ACRYLIC RESINS IN DENTISTRY

Poly (methyl methacrylate) (PMMA) (2, 4) is the polymer that is most commonly used in dental laboratories with diverse applications, whether in prosthodontics (for the development of interim rehabilitations, removal partial dentures, implant-supported dentures) or in other areas where they are used to create occlusal splinters and interceptive or containment orthodontic appliances (2, 3, 7).

Acrylic resins based in PMMA acquired popularity due to their natural appearance and the assurance of durability for the patient. Their widespread can be attributed to features such low density, ease processing method, favourable mechanical and aesthetic properties, acceptable cost- effectiveness and low toxicity (2, 8).

1.1.1. Composition

The full IUPAC (International Union of Pure and Applied Chemistry) chemical name for PMMA is poly (methyl 2-methlypropenoate). It is a synthetic polymer formed through the addition of free radicals and the polymerization of methyl methacrylate ($C_5O_2H_8$) into poly (methyl methacrylate) $(C_5O_2H_8)_n$ (2).

The polymerization reaction is initiated and activated by N, which generates an either free radical through chemical means (agent as dimethyl-p-toluidine) or energy input (such heat, light or microwaves) and origin free monomers. These act at the vinyl group of MMA, opening the carbon double bond and forming a new carbon-carbon single bond. During the propagation stage, the activated polymerization progresses by the binding of monomers, followed by termination through the relocation of free electrons to the chain end (9, 10).

Several mechanisms can terminate the polymerization reaction, including the addition of chemical inhibitors (such hydroquinone or methyl-ether) or the addition of monomers that react with free radicals. Additionally, any impurities present in the monomer may inhibit the polymerization by reacting with the free radicals (2, 9, 10).

PMMA is conventionally available in the form of powder-liquid system (Table 1 and 2) (11, 12).

Table 1. *Composition of the liquid and respective function*

Liquid (monomer)	
*MMA	
Hydroquinone or methoxy phenol	Polymerization inhibitor
N,N dimethyl-p-toluidine, tertiary amines, sulfuric acid	Polymerization accelerator
**EGDMA, TMPT, 1.4-BDMA, 1.6-HDMA	Polymerization cross-linker

*MMA–methyl methacrylate; **EGDMA–ethylene glycol dimethacrylate; TMPT–trimethylpropane trimethacrylate; 1.4-BDMA – 1.4-butanediol dimethacrylate; 1.6-HDMA–1.6-hexanediol dimethacrylate

Table 2*. Composition of the powder and respective function*

Powder (polymer)	
*PMMA, PBuMA, PEMA	
Dibenzoyl peroxide	Polymerization initiator
Dibutyl-,diethyl- and dicyclohexyl phthalate	Plasticizers
Colours, pigments and fibers of organic origin that simulate oral tissues and blood vessels	

*PMMA-poly (methyl methacrylate); PBuMA-poly(butyl methacrylate); PEMA-poly(ethyl methacrylate)

1.1.2. Types of PMMA

According to the polymerization process, it is possible to distinguish various types of acrylic resins. As per Specification No. 12 of the American Dental Association (ADA) (Table 3) (13), prosthetic base polymers undergo classification based on their polymerization reaction activation and composition. The specified types are type I (heat-cured), type II (self- cured), and type III (injected molded). In an expansion beyond these initial classifications, ISO 20795-1:2013 presented Type IV (light-cured) and Type V (microwave-polymerized) polymers (14).

Table 3. *Denture base polymers according to polymerization reaction and ADA Specifications*

Polymerization Reaction	***ADA Specifications***
Heat-cured	Type I – Heat processed
Self-cured	Type II – Auto-polymerized
Injected molded	Type III – Thermoplastic resin

1.1.2.1. Heat-cured

Heat-cured resins are commercially available in a powder/liquid formulation. The powder component compromises PMMA granules, benzoyl peroxide (serving as the initiator of the polymerization reaction), pigments, opacifiers (including titanium and zinc oxide), a plasticizing agent (such as dibutyl phthalate) and synthetic fibers (Table 2) (11, 12). The liquid component contains MMA, hydroquinone (acting as an inhibitor of the polymerization reaction), and ethylene glycol dimethacrylate, functioning as the cross-linking agent (Table 1) (11, 12). These resins are widely used and exhibit good mechanical properties due to its high degree of polymerization. Nonetheless, its principal drawback is high polymerization shrinkage, which may result in discrepancies concerning the adaptation to supporting tissue and the potential to discoloration (15). The most commonly used source of heat for polymerization is a water bath (10).

1.1.2.2. Self-cured

Self-cured resins are alternatively designated as cold polymerized, or chemical activated resins. The initiator for polymerization is a chemical agent specifically a tertiary amine (dimethyl-p-toluidine) (Table 1), which is added to PMMA to activate benzoyl peroxide (Table 2) (11, 12). The polymerization achieved by this method typically yield polymers of lower molecular weight, resulting in diminished mechanical properties and a higher monomer content, thereby increasing the risk of allergic reaction and decreasing colour stability. Nevertheless, these resins offer benefits such as enhanced dimensional stability, facilitating improved tissue adaptation due to reduced polymerization shrinkage. Despite their advantages, the inherent limitations of these resins render them primarily suitable for interim partial prostheses and their subsequent repair or relining procedures (10).

1.1.2.3. Light-cured

Light-cured resins are similar to composite resins. Their matrix is composed of urethane dimethacrylate (UDMA), and they contain a photoinitiator (e.g. camphorquinone). Polymerization occurs using a blue light chamber with a wavelength between 400 – 500 nm (4). They offer easier fabrication, complete control of polymerization, providing sufficient time for manipulation and adaptation before polymerization begins. The presence of residual monomer and polymerization shrinkage are reduced. However, their use is limited due to restricted depth of polymerization, technical sensitivity and high cost (2, 4). This type of resin also demonstrates inferior mechanical properties compared to thermopolymerizable resins. The application of these resins is limited to relining and repairing prostheses, as well as the fabrication of individual trays and base plates (4).

1.1.2.4. Injected molded

Thermoplastic materials such as polyamide, polycarbonate, and polypropylene and polyethylene terephthalate have been introduced in the field of dentistry as substitutes for traditional resins; primarily to address the latter's issue of residual monomer toxicity. They are available as single-components systems, dispensed individually, and have increasingly emerged as a preferred choice for removable partial dentures. These resins are distinguished by their absence of monomers, thereby making them non-toxic, non-allergenic, biocompatible, aesthetically pleasing, and enhancing patient comfort during usage. However, they present certain limitation that limit their application, including limited colour stability, greater microbial adhesion, complex technique and difficulty in repairs or relining (16, 17).

1.1.2.5. Microwave - polymerized

Microwave-polymerized resins present physical properties, dimensional stability and amount of residual monomer similar to heat-cured resins (18, 19). However, physical properties as impact and flexural resistance are described to be reduced (9). These resins require a source of microwave radiation and the use of non-metallic flasks. As advantages, they have a shorter polymerization time, good colour stability and improved adaptation to supporting tissues (2). Conversely, they demonstrate lower bond strength between teeth and prosthetic base material and require the use of non-metallic flasks, which, despite being more expensive, fracture more easily (5).

1.1.3. Properties of PMMA

Biofunctionality is crucial to ensure the success of prosthodontic rehabilitations, as it is necessary for materials to be biocompatible with surrounding tissues and to be capable of adapting to complex oral environments. In this context, the use of PMMA as a material for prosthetic bases is based on its biocompatibility, which is a crucial factor to avoid irritation, toxicity and mutagenicity in oral tissues (10). Additionally, it is crucial that the resins used in prosthetic manufacturing be insoluble in oral fluids and saliva, not interact with chewing forces and present high elasticity and fatigue modulus, impact resistance, and resilience (2, 10).

Table 4. *Ideal properties for acrylic resins*

PROPERTIES	CHARACTERISTICS
Mechanical	Fracture toughness; Impact resistance; Fatigue resistance; Abrasion resistance; High elasticity modulus
Biological	Biocompatible; Non-toxic; Non-irritating; Non-carcinogenic; Non-teratogenic
Chemical	Non-reactive; Insoluble; Low density
Physical	Low porosity; Dimensional Stability; Good thermal conductivity; Thermal stability; Thermal coefficient expansion similar to dental components; Radiopacity
Aesthetic	Ability to apply pigments; Translucency
Others	Good cost-effectiveness; Easy maintenance; Easy handling repair

Resins based on PMMA are commonly used due to the natural appearance they confer and their notable durability. Their widespread usage is attributed to characteristics such as low density, ease of processing, mechanical and aesthetics properties, acceptable cost-effectiveness ratio and low toxicity (2).

However, this resin is not considered an ideal polymer due to certain weakness in its mechanical and physical properties (4). The ease of water absorption compromises its mechanical properties during function, making the material vulnerable to fracture (2, 20, 21). Furthermore, some studies report that the conversion of MMA to PMMA is not a complete reaction, so it is possible to find residual monomer in the acrylic resin, which may reduce the potential of its properties and be one of the casual factors of inflammatory, allergic, and oral mucosa irritation responses (22-25).

Numerous studies have been undertaken to mitigate these drawbacks and unfavourable factors linked to PMMA (2, 4, 23).

1.2. COMPUTER-AIDED DESIGN / COMPUTER-AIDED MANUFACTURING (CAD/CAM)

One of the main disadvantages related to conventional processed PMMA is associated to its mechanical properties. The conventional method to obtain PMMA is associated to substantial polymerization shrinkage, reduced elastic modulus, impact and fatigue resistance and flexural strength, contributing to a heightened susceptibility to fracture (26). The propensity to fracture due to inadequate fatigue resistance arises from the stress that accumulates over time, particularly in regions submitted to chewing forces (26, 27). The release of residual monomer, methyl methacrylate (MMA), is also described as a drawback (20), affecting its dimensional stability and promoting porosity, which facilitates the colonization of oral microorganisms, like Candida Albicans (26, 28-30).

Additionally, this release can enhance allergic reactions, including stomatitis, edema and mucosal ulceration (24, 26).

The CAD/CAM technology has primarily been employed for the manufacture of fixed ceramic prosthetic restorations, for example, onlays, inlays, veneers and crowns. Further advancements in this technology over the last decade have provided means to obtain alternative restorative solutions using materials like composite resin, PMMA resins and metal blocks. Nowadays, it is also used for the fabrication of implant-supported prostheses, implant abutments and removable prostheses (20, 21, 25).

The designation CAD/CAM refers to computer-aided design and manufacturing, as CAD software creates the geometric shape of an object, and, consequently, CAM software corresponds to the final production phase and the acquisition of the physical object (25).

The system compromises the following functional components: (1) a data acquisition system that transforms volumetric surface information into digital data (intraoral or extraoral scanner); (2) CAD software responsible for processing the data to generate the 3D object and all its technical specifications; (3) physical object production technology, additive or subtractive, based on virtual data (25).

These are being implemented in Dental Medicine for the process of removable prosthesis, interim prosthetic rehabilitations and implant-supported prostheses. Dentures manufactured through this method has been introduced to reduce clinical procedures, enhance the replication of prostheses, optimize dimensional accuracy and improve surface properties, particularly addressing the porous surface and limited durability related to traditional dentures (8, 24, 31). The enhanced surface characteristics relative to conventional PMMA could be associated to the distinctive process technique employed for CAD/CAM PMMA (2, 31-33). Al-Dwari et al. (34) conducted a comparative analysis involving three groups of resins (a conventional heat-cured resin and two milling resins). The comparison revealed statistically differences ($p<0.05$) in mean roughness values between the conventional and the CAD/CAM resins.

1.2.1. Additive manufacturing or 3D printing

The additive process, commonly referred to as 3D printing, is defined by ISO/ASTM 52900 standards (35, 36) as the process of joining materials to form parts of a 3D model, typically, layer by layer. Additionally, the same standard defines 3D printing as the manufacturing of objects by deposing material using a print head, a nozzle or any other type of technology (35, 37).

The materials available for the use in 3D printing vary according to the technology and purpose of the printed objects. The most commonly used materials in additive manufacturing in Dentistry include polymers, metals and ceramics. Polymers have been increasingly used because of their versatility: try-ins, surgical guides, oclusal splints, denture bases, artificial tooth, custom tray, etc. (2, 12).

Three-dimensional printing technology is being implemented in denture base manufacturing and brings additional benefits. It offers great-cost effectiveness, eliminates the wear of rotatory instruments, reduces waste of raw materials and allows the simultaneous production of multiple products (24). However, there is a lack of evidence regarding, mechanical properties, clinical performance and a long-term patient follow-up. A high rate of contraction during the polymerization process is described, comprising its biocompatibility (2, 24, 34, 37, 38).

1.2.2. Subtractive manufacturing or Milling

The manufacturing of pre-polymerized discs for subtractive processes aims to enhance material quality by reducing reliance on operators (24). High pressure and temperature are used in the production of pre-polymerized blocks for subtractive manufacturing (8, 24, 31). This manufacturing technique employs a CNC (computer numerical control) milling machine responsible to carve products from solid blocks until the desired geometry is obtained. CAM software translates CAD design into precise tool path, dictating the milling process, such as sequencing, tool selection and tool motion direction and magnitude. Prosthetic rehabilitation milling machines accommodate anatomical variation by combining burs of different sizes. The accuracy of milling is demonstrated to be within a range of 10 μm (31, 38).

This process promotes the development of longer polymer chains that enhance a higher degree of monomer conversion and lower residual monomer content. It is expected that milled PMMA present higher mechanical properties (24).

1.3. SURFACE ROUGHNESS

Surface roughness is a highly relevant clinical factor, as it directly or indirectly affects the retention of microbial plaque on tissues in contact with materials, increasing the risk of surface fatigue and decreasing its biocompatibility. Surface roughness on hard surfaces has a significant impact on the retention of microorganisms; therefore, the literature describes that rough surfaces tend to promote the adhesion of microbial plaque when compared to smooth surfaces (28).

In the case of acrylic resins, the value of surface roughness is influenced by inherent characteristics of the material, the polishing technique and the manual skill of the operator. The reported value characteristic of a polished acrylic surface is 0.12 μm;

however, typically the threshold is located between 0.03 µm and 0.75 µm (28, 39-41). In 1997, Bollen et al. (28) proposed a threshold without significance for bacterial colonization of 0.2 µm.

Studies at both supragengival and subgingival levels reveal that an increase in surface roughness contributes to higher rates of surface colonization and greater maturation of microbial plaque, increasing the risk of developing caries and inflammation of periodontal tissues (29, 42). Additionally, *Candida albicans* is one of the main microorganisms recognized as an etiological factor for inflammatory mucosal changes, such as prosthetic stomatitis, due to the use of denture base acrylic resins, as the association between surface roughness and retention of this microorganism has been demonstrated (29).

1.3.1. Surface roughness measurement

Surface roughness measurement equipment is classified into two groups: contact and non-contact (43-45). Profilometers are the most commonly used contact instruments to measuring surface roughness, quantifying it based on the recorded surface height. The principle of the device involves a diamond tip in contact with a surface that performs a straight-line scan, where height variations are converted into electrical signals, referred to as micrometric magnitudes. The measurements obtained represent only two dimensions (2D), as the tip moves vertically and horizontally along a central line (43, 46, 47). In a graphical perspective, surface roughness corresponds to height variations on a surface relative to a reference plane (43, 44).

One factor to consider is the diameter and shape of the tip of this equipment in determining the sensitivity of the measurements since it’s not possible to measure roughness with a dimension smaller than the diameter of the instrument’s tip. Another aspect is the pressure exerted by the tip on the surface of the object due to the induction plastic deformation of the surface if it exerts a force greater than that tolerated by the material. Since the deformation is identical across the entire surface, it must be ensured that the instrument's tip does not lose contact with the surface during its movement (44).

The most commonly referenced non-contact instruments are the optical profilometer and the scanning electron microscope (SEM) (43, 44). The optical profilometer emits a light beam at 45º angle onto the surface to be measured, allowing for surface measurements in horizontal, vertical or any other orientation (43). Smooth surfaces result in a straight image; however, when the surface is rough, the image will display waviness (43, 44). The SEM enables the acquisition of topographical images of material surfaces (44, 48, 49). Images are obtained through image acquisition and processing software, facilitating profile analysis, roughness parameters calculation and various measurements (48, 49). The interpretation of images and surface roughness measurements is based on the grayscale intensity. Depending on the microscope's resolution, it is possible to analyse roughness at various scales, yielding results ranging from micrometric to nanometric (43, 44).

1.3.2. Analysis of surface roughness

Surface texture refers to the repetitive or random deviations from the intended surface, shaping its three-dimensional topography (18). A surface profile can be conceptualized as a waveform, comprising a high-frequency component (roughness) and two-lower frequency components (waviness and form errors) (46, 50). Nano- and macro roughness emerge from surface fluctuations of short wavelengths, featuring hills (asperities) and valleys (local minima) of varying amplitudes (50).

Profile graphs do not directly provide the quantitative data necessary to estimate the functional value of a surface. Such data can be derived from a surface profile graphs through the analysis of statistical parameters. These parameters quantify the vertical (amplitude), horizontal deviations (spatial) or a combination of both amplitude and spatial aspects (44, 46, 47).

Surface roughness parameters have been stablished and standardized by the American National Standard Institute (ANSI) (51) and the International Organization for Standardization (ISO). ISO 4288:1996 has presented rules and procedures to assess surface texture (50).

1.3.3. Terminology

For standard surface profile measurements (52), the surface roughness is divided into two parts: the surface roughness profile (P) and the waviness profile (W), each representing distinct aspects of the surface shape (45). A roughness profile (R) is created by removing the long wavelength (λc) component from a primary profile (P) and a waviness profile (W) is created by removing the short-wavelength component from the primary profile (P).

Applying the concepts delineated within table 5: the sampling length of the roughness profile (R) are equivalent to their cut-off values (λc). However, when assessed the primary profile (P), the sampling length (λc) is equivalent to the profile's evaluation length (lm) (Table 5). Generally, an evaluation length (lm) is five times the corresponding sampling length (λc) (47) (Figure 2).

Table 5. *Surface roughness terminology*

Term	Definition
Surface primary profile (P/ lt)	A curve that appears when a surface of a material is cross-sectioned.
Sampling length (λc)	Roughness parameters are determined based on the extracted part of a given length from the profile.
Evaluation length (lm)	A part of a given length extracted from the profile to determine roughness parameters.
Cut-off value (λc)	A predetermined wavelength to be removed from a primary profile.

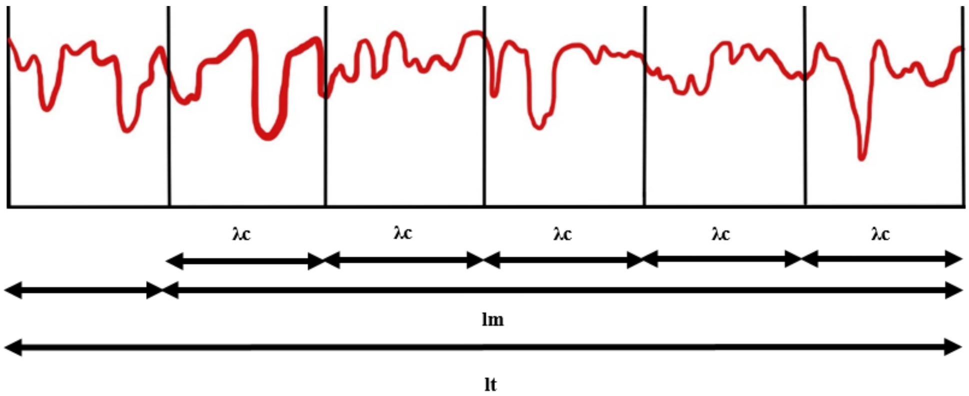


Figure 2. Primary profile (lt); Roughness profile (lm); Gaussian filter with a cut-off length (λc)

*Figure published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*).

1.3.4. Cut-off selection (λc)

The cut-off refers to the predetermined wavelength to be removed from the primary profile (P). The cut-off wavelength (λc) pretends to remove all components of the primary profile that have wavelengths greater than cut-off value (47).

In order to establish a standardized methodology for quantifying surface roughness, a range of cut-off wavelength values have been defined by ISO 4287:1998 (52) (Table 6). This standard typically sets cut-off values at 0.08mm, 0.25mm, and 0.8 mm. The default cut-off value of 0.8mm is typically applied unless alternative specifications are provided (50).

Table 6. Relationship between the cut-off length (λc) and transverse length (lt)

Cut-Off (λc) mm	Transversing Length (lt) mm
0.08	0.48
0.25	1.5
0.8	4.8
2.5	15.0
8.0	48.0

All surface roughness profiles are calculated from a filtered surface profile. The correct selection of the filter parameter (the cut-off length λc) is important to the validity of the measurement (46, 47).

The long-wave cut-off wavelength interval for surface roughness is 4.5 µm to 25 mm, and the short-wave cut-off wavelength ranges from 0.25 µm to several millimetres (50). In the literature, the cut-off selected for surface roughness on acrylic resins is chosen according to the expected threshold for microbial colonization (Ra = 0.2 µm) (ISO 4288; 1997) (28, 34, 54).

1.4. SURFACE ROUGHNESS PARAMETERS

1.4.1. Amplitude parameters

The most important parameters to characterize the surface topography are the amplitude parameters, serving as a fundamental measure for quantifying the vertical attributes of surface irregularities (55).

The arithmetical mean height corresponds to the arithmetic average of the absolute height values on the Y-axis (X) from the centerline (47, 55).

The corresponding mathematical formulation as described in ISO 4287:1997 (52) for surface texture (Table 7). Each parameter is classified according to primary profile (P), roughness profile (R) and waviness profile (W) to evaluate different aspects of the profile.

The arithmetic mean roughness (Ra) refers to the filtered profile (lm), through a cut-off wavelength (λc). In contrast, the arithmetic mean height (Pa) refers to the primary unfiltered profile (lt) (Figure 2).

Table 7. *Arithmetic mean roughness (Ra) and Arithmetic mean height (Pa)*

Parameter	Description	Formula
Ra	Arithmetic mean roughness	$\frac{1}{l_m}\int_0^{l_m} \lvert y(x)\rvert dx$
Pa	Arithmetic mean height	$\frac{1}{l_t}\int_0^{l_t} \lvert y(x)\rvert dx$

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*)

1.4.2. Statistical parameters

Profile graphs alone lack the quantitative data necessary for estimating the functional value of a surface. Extracting such data from surface profile graphs involves analysing statistical parameters (46, 50). In the computerized surface profile analysis, a key initial process involves converting the analog or continuous transducer signal, which represents the surface profile, into a set of numerical data points. These numerical data points are referred to as profile height ordinates. The conversion task is dictated by an Analog to Digital Converter (ADC). After the numerical capture of surface profile data, it is processed and analysed as a statistical dataset (21). These parameters quantify vertical (amplitude), horizontal deviations (spatial) or a combination of both amplitude and spatial aspects (46, 50). The amplitude distribution curve is a graphical representation of the distribution of ordinate heights over the total profile depth. The characteristics of the amplitude distribution curve are defined as moments (47).

Based on the aim of this research, the authors focused on the third and fourth moment on the amplitude distribution curve, skewness and kurtosis, respectively (47, 55).

1.4.2.1. Skewness

Skewness is a function of the cube of the ordinate height, though it is extremely sensitive to the ordinate height value (47). The skewness of a profile denotes the symmetry of the amplitude distribution curve to profile mean line.

A skewness of zero indicates a roughness profile exhibiting a Gaussian distribution. When the skewness is negative, the surface exhibits an elevated occurrence of local maxima above the mean, deviating from the symmetrical pattern of a Gaussian distribution. Conversely, positive skewness results in the opposite effect characterized by a surface with high peaks and filled valleys (46, 47, 50, 56) (Table 8). In resume, a negative value of Rsk indicates that the surface is made up of valleys, whereas a surface with a positive skewness is said to contain mainly peaks and asperities.

Table 8. *Skewness*

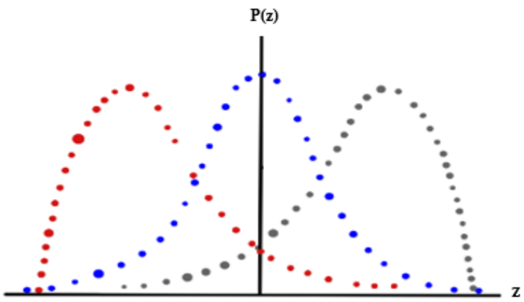
Value	Meaning	Graphic representation (50)
Rsk < 0	Longer tail on the left of the distribution (grey curve)	
Rsk = 0	Symmetrical Gaussian distribution (blue curve)	
Rsk > 0	Longer tail on the right of the distribution (red curve)	

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*).

1.4.2.2. Kurtosis

Kurtosis is a function of the fourth power of the profile ordinates, though it is extremely sensitive to large peaks and valleys (47).

It describes the sharpness of the probability density in the profile. A roughness profile demonstrating a Gaussian distribution corresponds to a kurtosis value of 3. A pronounced amplitude distribution compared to a Gaussian distribution curve signifies substantial, sharp peaks and valleys in the surface profile with Rku values exceeding 3. Conversely, surface with a reduced occurrence of extreme values compared to a Gaussian distribution is indicated by a kurtosis below 3 a flat distribution curve with surfaces featuring numerous small, rounded peaks and valleys in the surface profile opposite (46, 47, 50, 56) (Table 9).

Table 9. *Kurtosis*

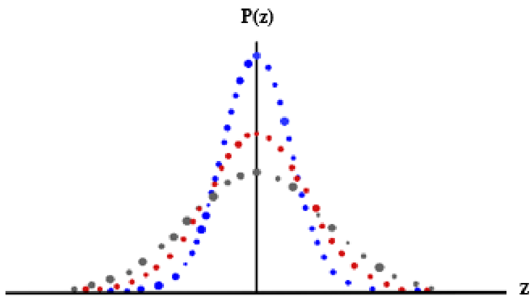
Value	Meaning	Graphic representation (50)
Rku < 3	Flat amplitude distribution (grey curve)	
Rku = 3	Symmetrical Gaussian distribution (blue curve)	
Rku > 3	Sharp amplitude distribution (red curve)	

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*).

1.5. SURFACE HEIGHT DISTRIBUTION

The height distribution is represented by the height probability density that assess the probability of a specific surface height relative to the centreline.

In addition to average roughness values, the comprehensive analysis of skewness and kurtosis should be considered to provide information about the distribution of irregular heights across the surface (46, 57), the symmetry of texture's amplitude and the determination whether it exhibits unusually high peaks/valleys on the surface, with influence on bacterial adhesion (29, 46, 50, 58, 59) .

The surface height distribution exhibits a degree of randomness that can be categorized as either isotropic or anisotropic and may follow a Gaussian or non- Gaussian distribution. For example, surfaces generated through cumulative processes, as 3D printing processes result of numerous random discrete local events, the overall effect tends to follow a Gaussian pattern (Rsk= 0 and Rku= 3). Shaping processes, like grinding and milling lead to a non- Gaussian pattern with pronounced grooves, negative skewness and high kurtosis values (46).

The Gaussian (normal) distribution has become a fundamental tool for classifying surface properties (46, 50, 60).

1.6. POLISHING PROTOCOLS

Acrylic resins can experience changes influenced by both internal and external factors, including the presence of residual monomers and absorption. Effective management of biofilm is essential for maintaining the longevity of prostheses and preserve patient's oral health (41, 61).

The recommended approach often involves a combination of mechanical and chemical techniques (62, 63). Denture acrylic resins should undergo gradual polishing to remove rough layers, resulting in smoother surfaces and reduced surface energy. An optimal surface roughness threshold of 0.2 μm is identified to facilitate biofilm control and minimize microorganism adherence (63). Mechanical polishing employs various tools such as polishing wheels, felt cones, rubber, and silicone polishers along with abrasive pastes like aluminium oxide and pumice. This technique presupposes the reduction of surface irregularities through controlled abrasion. The effectiveness of mechanical methods compared to chemical alternatives has been well documented. The chemical procedures directly affect the mechanical resistance of the resins, increasing the risk of deformation (62-64).

The surface roughness of these materials is primarily determined by the inherent characteristics of the materials, the polishing method used and the operator's skills (39-41). The resins denture base polymers and the polishing method are regulated by ISO Standards (65). Although, it does not address the operator's related skills. Nowadays, if the mechanical polishing procedure for acrylic resins is considered, two methodologies are described in the literature, one dependent on the operator and another independent (39-41, 63).

1.6.1. Mechanized Protocol

The initial attempt to address this constraint was made by the Corsalini et al. (39). The authors introduced a standardized approach to polishing denture base acrylic resins irrespective of individual operator proficiency. The establishment of a standardized protocol would ensure operation repeatability and consistency, thereby enabling a uniform comparison of the different resin types (39, 40).

Corsalini et al. (39) proved that polished mechanically specimens demonstrate a quasi-normal Gaussian distribution in contrast with those polished manually which exhibit a clearly asymmetric distribution. The data suggested that a protocol reliant on mechanical polishing could be standardized more easily compared to manual polishing procedures.

The suggested polishing protocol had the following assumptions (39, 40):

1. The fixation of the study samples on a support.
2. The parallelism between the samples and the polishing drill.

3. The horizontal direction of the movement.

4. The constant speed determined by the micro-motor.

In 2022, Quezada et. al. (41) developed a prototype of a “mechanized operator” in the Faculty of Engineering of University of Porto with the aim of calibrating and standardized the polishing method in clinical practice. While Corsalini et al. (40) methodology entailed the utilization of a laboratory instrument customized for polishing, the authors developed a portable instrument printed in 3D resin for use in a chairside setting - a Control Polishing Tool (CPT) (Figure 3) (41). Both mechanisms follow the same assumptions.

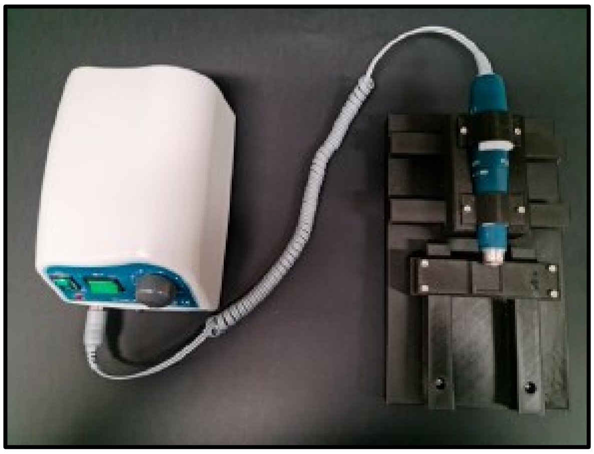


Figure 3. *Control Polishing Tool (CPT)*

*Figure published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach To Analyzing The Surface Roughness Of Prosthetic Dental Acrylic Resins. App. Sci. 2024 Jan;14(2): 619*).

The portable device consists of two platforms (41, 66):

- The first platform secures the handpiece, maintaining consistent pressure on the samples during polishing.
- The second platform stabilizes the sample with the predefined dimensions.

The first platform moves along the sample, while the positioning of the handpiece relative to the instrument's base guarantees parallel polishing of the sample surface to the support.

A proof of concept was conducted (66). The distribution of roughness values between the control group (samples not submitted to polishing protocol) and the arithmetic mean roughness (Ra) obtained by the CPT protocol differed significantly ($p = 0.004$).

Despite its viability (41, 66), the effect of a "standardized polishing protocol" on the distribution of surface heights remains a lack in the knowledge, thereby, testing its effect in terms of uniformity.

2. OBJECTIVES AND JUSTIFICATION

Acrylic resins are the most commonly used material to manufacture prostheses, orthodontic appliances, and temporary fixed restoration in dentistry, leading the market trend towards obtaining materials with improved properties and characteristics to overcome the limitations of existing ones. The advancement of Digital Dentistry through the introduction of CAD/CAM technologies allowed to obtain acrylic resins and proved to be a viable option to overcome the disadvantages associated with conventional resins.

In the specific case of removable prostheses, the choice of resin type and polishing technique become crucial for aesthetic, longevity, and clinical success. The study of surface properties, such as roughness, should be carried out using specific and targeted parameters for the evaluation of its clinical relevance. Roughness parameters depend on inherent materials characteristics, the polishing method employed and the manual skill of the operator that directly influence the interaction between the denture base acrylic resins and the development of oral cavity pathologies, such as Oral Candidiasis and/or Denture Stomatitis.

The specific objectives of this research were:

1. To validate a new approach for the analysis of surface roughness height parameters.

2. To understand the influence of acrylic resin processing techniques based on the surface roughness height parameters.

- **2.1.** To understand the differences produced in the surface roughness height parameters between conventional and CAD/CAM processing techniques of acrylic resins
- **2.2.** To understand the proper selection of polishing protocols based on the surface condition immediately after processing.

3. To understand the influence of acrylic resins polishing protocols on the surface roughness height parameters.

3.1. To evaluate the feasibility of a mechanized tool in terms of standardizing the polishing protocol.

3. OBJETIVOS Y JUSTIFICACIÓN

Las resinas acrílicas son el material más comúnmente utilizado para fabricar prótesis, aparatos ortodónticos y restauraciones fijas temporales en odontología, lo que lidera la tendencia del mercado hacia la obtención de materiales con propiedades y características mejoradas para superar las limitaciones de los existentes. El avance de la odontología digital mediante la introducción de tecnologías CAD/CAM permitió obtener resinas acrílicas y demostró ser una opción viable para superar las desventajas asociadas con las resinas convencionales.

En el caso específico de las prótesis removibles, la elección del tipo de resina y la técnica de pulido se vuelven cruciales para el éxito estético, la longevidad y clínico. El estudio de las propiedades de la superficie, como la rugosidad, debe llevarse a cabo utilizando parámetros específicos y dirigidos para la evaluación de su relevancia clínica. Los parámetros de rugosidad dependen de las características inherentes de los materiales, del método de pulido empleado y de la habilidad manual del operador, que influyen directamente en la interacción entre las resinas acrílicas de la base de la dentadura y el desarrollo de patologías de la cavidad oral, como la candidiasis oral y/o la estomatitis protésica.

Los objetivos específicos de esta investigación fueron:

1. Validar un nuevo enfoque para el análisis de los parámetros de altura de la rugosidad de la superficie.

2. Comprender la influencia de las técnicas de procesamiento de resinas acrílicas en función de los parámetros de altura de la rugosidad de la superficie.

2.1. Comprender las diferencias producidas en los parámetros de altura de la rugosidad de superficie entre las técnicas convencionales y CAD/CAM de procesamiento de resinas acrílicas.

2.2. Comprender la selección adecuada de protocolos de pulido en función de la condición de la superficie inmediatamente después del procesamiento.

3. Evaluar la viabilidad de una herramienta mecanizada en términos de estandarizar el protocolo de pulido.

3.1. Evaluar la viabilidad de una herramienta mecanizada en términos de estandarizar el protocolo de pulido

4. MATERIALS AND METHODS

The present "*in vitro*" experimental research was conducted in collaboration with the Faculty of Engineering of the University of Porto (FEUP) and with the Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI).

4.1. MATERIALS

4.1.1. Study sample

The study sample consisted of 30 specimens with standardized dimensions suitable for the analysis of surface roughness parameters (Table 10).

Table 10. *Samples dimensions*

Shape	Length	Width	Thickness
Square	20 mm	20 mm	3 mm

This research examined five types of acrylic resins for prosthetic bases (Table 11).

Table 11. *Description of the resins used*

Name	Commercial brand	Country of origin
Probase® cold	Ivoclar Vivadent	Liechtenstein
Probase® hot	Ivoclar Vivadent	Liechtenstein
iflex™	tcs®	USA
CediTEC DB	VOCO® GmbH	Germany
V-Print dentbase	VOCO® GmbH	Germany

* Table published on Paper 2 (*Quezada MM, Fernandes CMdCG, Martín JM, Correia ARM, da Fonseca PAB. Influence of different processing techniques for prosthetic acrylic resins in the surface roughness parameters: a research article. BMC Oral Health. 2024;24(1):641*)

The manufacturer's instructions to obtain the acrylic resin samples are resumed in Table 12, and described below.

Table 12. *Characteristics of the resins*

Material	Composition		Ratio	Curing method
Probase® Cold	**P:** PMMA Dibenzoyl peroxide	**Li:** MMA	P/Li 20.5/10 (g/ml)	Self – curing: 23 ºC for 30 minutes (Conventional)
Probase® Hot	**P:** PMMA Dibenzoyl peroxide	**Li:** MMA 1-4 butanediol dimethacrylate	P/Li 22,5/10 (g/ml)	Heat – curing: 100 ºC for 45 minutes (Conventional)
iFlex™	Polyolefin		-	Injected molded (Conventional)
Ceditec DB	PMMA		99%	Milling (CAD/CAM)
V-Print dentbase	**Li:** UDMA Bis – EMA TEGDMA		 50 -100% 25-50% 5-10%	Digital light processing method (DLP) (CAD/CAM)

P – Powder; Li – Liquid; PMMA– Poly Methyl Methacrylate; UDMA– Urethane Dimethacrylate; Bis – EMA – Bisphenol-A-Ethoxylate Dimethacrylate; HEMA – Hydroxyethyl

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4.1.2. Acrylic resins processing method

For the manufacture of the samples, silicone molds with predefined dimensions were produced (20 x 20 x 3 mm) – Figure 4.

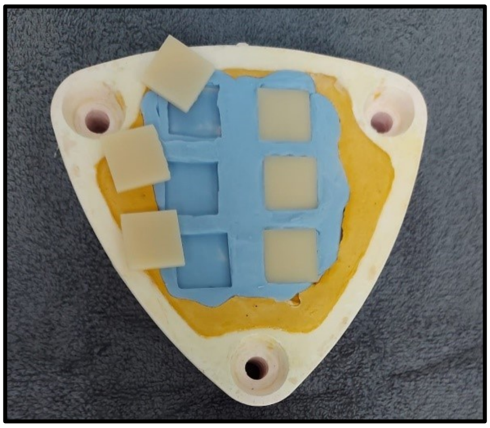

Figure 4. *Silicone molds with predefined dimensions (20 x 20 x 3 mm)*

*Figure published on Paper 2 (67) (*Quezada MM, Fernandes CMdCG, Martín JM, Correia ARM, da Fonseca PAB. Influence of different processing techniques for prosthetic acrylic resins in the surface roughness parameters: a research article. BMC Oral Health. 2024;24(1):641*)

4.1.2.1. <u>Self-cured</u>

1. Measurement of the polymer and self-curing monomer, powder, and liquid, respectively (Figure 5). Preparation of the mixture in an appropriate container (a glass dappen dish), according to the proportions specified by the manufacturer's instructions.

Figure 5. *Probase® Cold*

2. The powder was poured over the liquid and mixed using an acrylic spatula to ensure all particles were incorporated into the monomer.

3. To prevent air inclusion, the container was sealed until the mixture reached the stringy phase.

4. The mixture was placed into molds with a working time of 3-5 minutes at 23±2ºC.

5. Cure time: 10 minutes

4.1.2.2. <u>Heat-cured</u>

1. Production of wax squares with the predefined dimensions of the specimens (20x20x3 mm) and insertion into silicone mold.

2. Preparation of Type III gypsum with a ratio of 20ml water to 100 of powder.

Figure 6. *Probase® Hot*

3. Preparation of the mixture in an appropriate container (a glass dappen dish), according to the proportions specified by the manufacturer's instructions (Figure 6). The powder was poured over the liquid and mixed using an acrylic spatula to ensure all particles were incorporated into the monomer.

Pour the resin into the spaces in the silicone mold after removing the wax squares.

4. Cure process: Submersion of the closed flask in water at 73±1 ºC for 90 minutes. Subsequently, transfer the flask to boiling water for 30 minutes. The water temperature was periodically checked using a precision thermometer.

5. The flask was placed at room temperature for 30 minutes. Then, it was submerged in cold water for 15 minutes.

4.1.2.3. Injected molded

1. Production of wax squares with the predefined dimensions of the specimens (20x20x3 mm) and creation of a silicone mold with a channel system for resin passage.

2. Preparation of Type III gypsum with a ratio of 20ml water to 100 of powder. The mixture was placed at the base of the flask for subsequent inclusion of the silicone mold.

3. The thermoplastic resin tube was placed in the tcs® Digital Furnace (tcs® Digital Furnace, tcs® Dental Inc., Califórnia). The resin was injected into the molds using the tcs® Handheld JP90 (tcs® Dental Inc., Califórnia) – Figure 7. The polymerization reaction occurred at room temperature within the flask, approximately, 23±2 ºC.

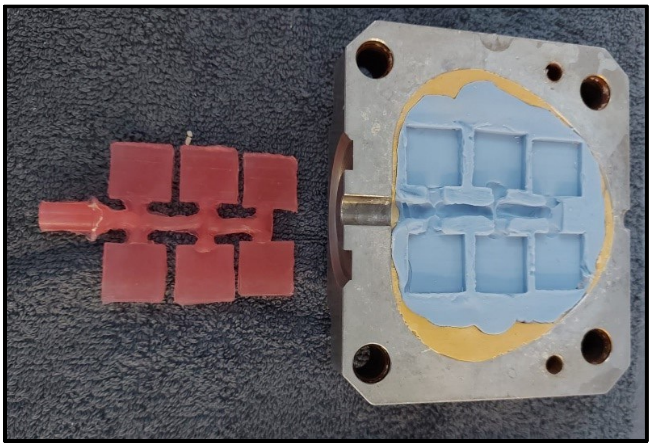

Figure 7. *Injection technique on the predefined silicone molds*

*Figure published on Paper 2 (67) (*Quezada MM, Fernandes CMdCG, Martín JM, Correia ARM, da Fonseca PAB. Influence of different processing techniques for prosthetic acrylic resins in the surface roughness parameters: a research article. BMC Oral Health. 2024;24(1):641)*

4.1.2.4. CAD/CAM Milled

1. Virtual design and milling of specimens: The specimens were virtually designed using the CAD software SolidWorks® (Dassault Systèmes SolidWorks Corporation, United States). The CAD design was converted to an STL (Standard Tessellation Language) file format. The STL file was sent to a DWX-52D milling machine (DWX Series, Spain).

2. Preparation and milling: A pre-polymerized PMMA block (CediTEC DB, VOCO® GmbH, Germany) with dimension of 98.5x30 mm was placed into an appropriately sized adapter. The cutting tool was positioned at a 90º angle relative to the PMMA block. The milling process was performed dry.

3. Static and debris management: The milling machine has a system to eliminate static electricity generated between the block and the cutting tool. A particle suction system ensures the cutting tool operates without debris on the surface.

4. Post-milling process: The disc was removed from the holder and the specimens were separated from the disc.

4.1.2.5. CAD/CAM 3D Printed

1. Virtual design and 3D printing of specimens (Figure 8): The specimens were virtually designed using the CAD software Asiga Composer (Asiga Composer, ASIGA, Germany). The CAD design was converted to STL file format and sent to the 3D printer (Asiga Max UV 3D Printer, ASIGA, Germany). The specimens were fabricated using digital light processing (DLP) method.

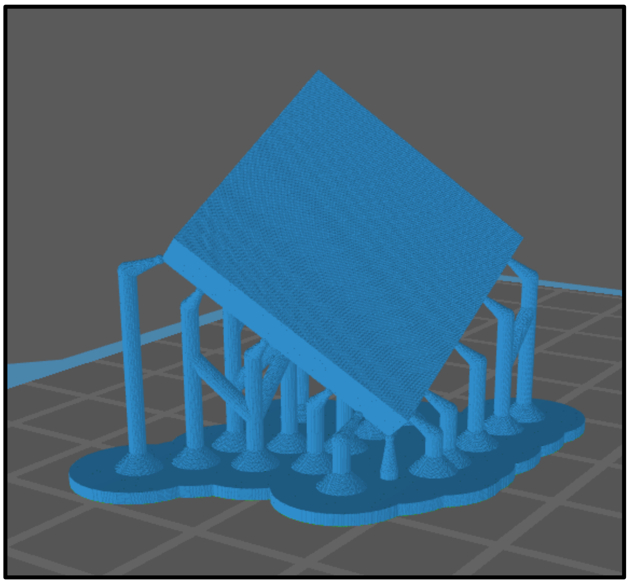

Figure 8. *3D printed sample: CAD design*

2. Ultrasonic Cleaning: The specimens underwent two ultrasonic baths with isopropyl alcohol, each lasting 2 minutes (Sonorex Super RK 102H, Bandelin, Germany), following the manufacturer's instructions.

3. Post-processing was carried out using a polymerization device (Otoflash G171, Flashing Unit, NK-Optik GmbH, Germany), which produces ten flashes per second with radiation in the wavelength range of 280-580 nm.

4. The specimens did not undergo any surface treatment.

The 3D-printed and milled acrylic resin samples were provided directly by VOCO® GmbH (VOCO® GmbH, Germany), so the obtaining procedure is only described and not graphically represented.

The samples were placed in sterilized, labeled and sealed sleeves to prevent any deterioration or contamination. The test specimens' quality was conducted according to the following criteria (Table 12).

Table 13. *Inclusion and exclusion criteria.*

Inclusion	Exclusion
- Specimens with pre-defined shape and dimension.	- Specimens with visible irregularities.
- Specimens without significant changes because of the polishing procedure.	- Fractured specimens.
	- Specimens damaged during the experimental protocol.

The evaluation was conducted through both visual inspection and precise measurement of predefined dimensions using an analog calliper (ROSTFREI GEHARTET calliper, Brütsch/Rüegger Tools Ltd., Urdorf, Switzerland) (Figure 9).

Figure 9. *ROSTFREI GEHARTET calliper*

The thirty specimens complied with the inclusion criteria.

4.1.3. JOTA® KIT 1877 DENTUR POLISHING

The polishing kit selected was JOTA® KIT 1877 DENTUR POLISHING (Jota AG, Rüthi, Switzerland) (Figure 10).

Figure 10. *JOTA® KIT 1877 DENTUR POLISHING*

The manufacturer's protocol recommends the selection of bullet-shape burs for denture base acrylic resins (Table 14).

Table 14. *Selected burs of the polishing Kit*

Code	Grain	Shape	Length (mm)	Diameter (mm)	Revolutions per minute (rpm)
9572G	Green	Bullet	23,00	10,00	5’000
9572M	Grey	Bullet	23,00	10,00	5’000
9572F	Yellow	Bullet	23,00	10,00	5’000
1164	-	Wheel	-	-	10’000

The polishing system consists of four steps: surface smoothing (bur 9572G – green grain), pre-polishing (bur 9572M – grey grain), polishing (bur 9572F – yellow grain) and high shine polishing (bur 1164 + emulsion 1150).

The manufacturer advises the burs to be used dry to prevent staining the acrylic. Each bur should be applied to polish the surface for 30 seconds.

4.2. METHODS

The present research is experimental and aimed to evaluate surface roughness height parameters of five groups of acrylic resins used for denture bases.

The study samples were organized into six groups: a control group, consisting of one specimen from each type of resin used in prosthetic bases and five study groups, each with five specimens, differentiated by the processing method used to obtain the acrylic resins (Figure 11).

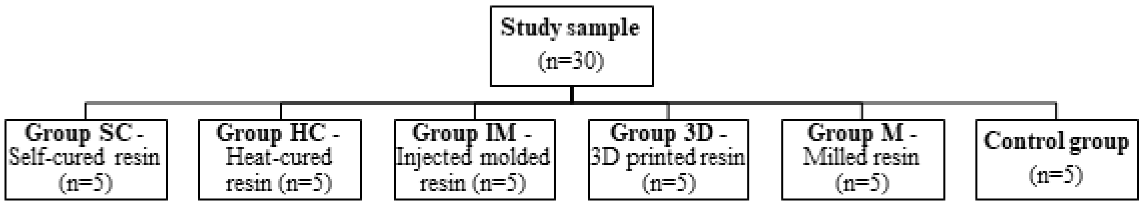

Figure 11. *Study sample distribution*

The specimens of the control group were not submitted to the polishing protocol (Figure 12). The study specimens were submitted to JOTA® KIT 1877 DENTUR POLISHING (Jota AG, Rüthi, Switzerland) (Figure 13).

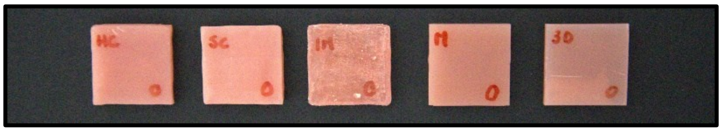

Figure 12. *Control group*

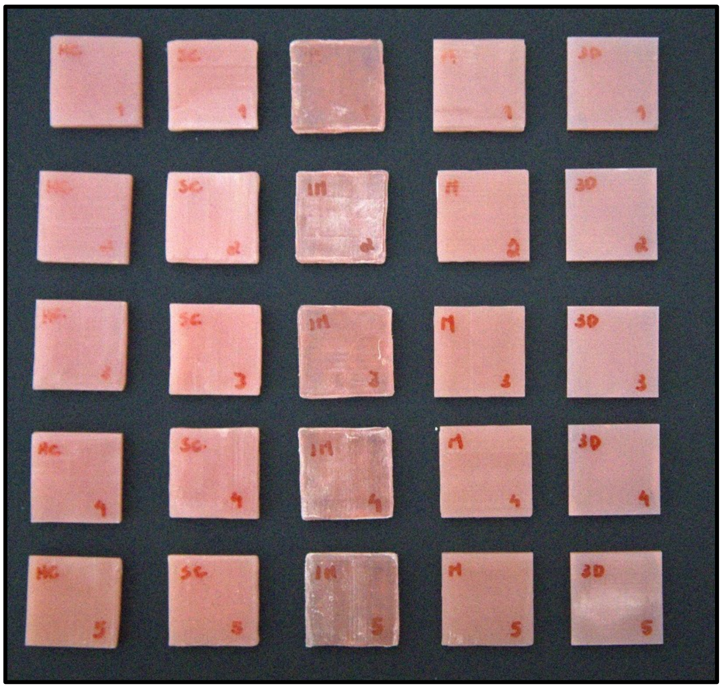

Figure 13. *Study group*

The investigation was conducted in two parts.

1. The first phase sought to address a discrepancy in roughness assessment identified by the authors in the literature (46, 50, 56, 68, 69). A proof of concept was conducted to validate a different approach for analysing surface roughness height parameters: arithmetic mean roughness (Ra), arithmetic mean height (Pa), skewness (Rsk/Psk) and kurtosis (Rku/Pku) (53).

<u>1.1.</u> Six samples of CAD/CAM 3D printed resin (VOCO GmbH, Cuxhaven, Germany) were submitted to analysis. Five samples were submitted to two polishing protocols, mechanized and manual and the sixth sample served as a control (without polishing). Arithmetic mean roughness (Ra), arithmetic mean

height (Pa), skewness (Rsk/Psk) and kurtosis (Rku/Pku) were extrapolated after profilometric reading.

2. Secondly, as previously described, surface roughness is directly dependent on the acrylic resins processing techniques and the polishing techniques (39, 41, 70). Following the validated evaluation approach, roughness parameters were measured immediately after the processing of the samples and after the application of the polishing protocols.

2.1. The control group (HC0, SC0, IM0, 3D0, M0) (Figure 12) was submitted to analysis to extrapolate the profilometric measurements (Pa, Psk, Pku) of the specimens directly resulting from the processing techniques.

2.2. The study group (HC1-5, SC1-5, IM1-5, 3D1-5, M1-5) (Figure 13) was subjected to a conventional and a mechanized method (CPT). The protocols influence on the profilometric measures (Pa, Psk, Pku) were acquired.

4.2.1. Polishing protocol

The study group followed the polishing protocol described by the authors (41). To reduce the wear of the polishing burs used between the study groups, five subgroups were composed, each containing one samples of each type of resin (e.g., subgroup 5 – HC5, SC5, IM5, 3D5, M5) (Figure 14).

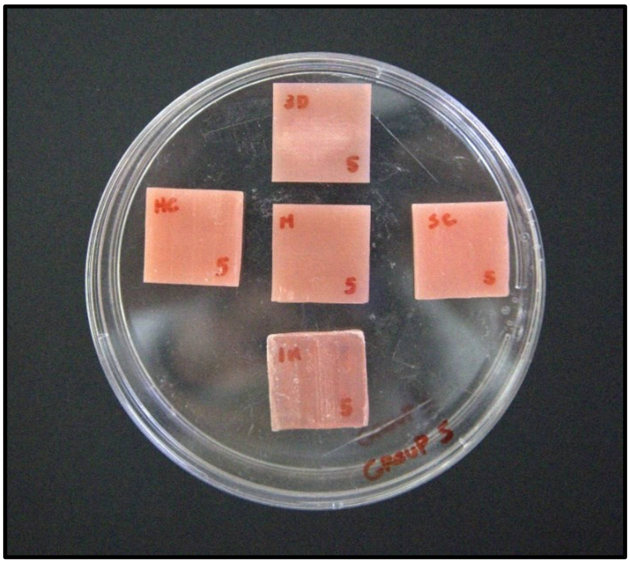

Figure 14. *Subgroup example*

All specimens were polished following the conventional steps specified in ISO standard 20795:2008 (65). The process involves using a tungsten carbide bur with a thin cross – cut followed by JOTA® KIT 1877 DENTUR POLISHING (Jota AG, Rüthi, Switzerland) sequence (Table 13) with a micro-motor coupled (STRONG 206, SAESHIN®, Daegu, Republic of Korea).

The JOTA® KIT 1877 DENTUR POLISHING was applied on the study group under two different techniques described by the authors (41, 53): a conventional, dependent of the human operator; and a mechanized, with a controlled polishing tool (CPT), not human dependent. The CPT protocol was described in a previous research (41).

To ensure consistent processing techniques conditions and reduce their influence on surface roughness, the same samples were used for both polishing techniques. The conventional method was applied to one side and the mechanized to the opposite side, randomly determined.

The polishing direction of the samples was consistently maintained. A single operator carried out the polishing protocol to minimize variability and ensure that the procedure was uniformly and independently applied to all tested resins, simulating the procedure executed in the chairside/laboratory conditions.

The samples were immersed in distilled water (Figure 16) and placed in an EHRET BK 4106 oven (EHRET GmbH, Germany) (Figure 15) at a constant temperature of 37 ºC for 24 hours. This procedure simulates the rehydration of the acrylic in prosthetic bases following the surface polishing procedure, in accordance with ISO 20795-1 (71).

Figure 15. *EHRET BK 4106 oven*

Figure 16. *Specimens immersed in distilled water inside the oven*

4.2.2. Surface roughness measures

Surface roughness measures were conducted using a contact profilometer (Hommelwerke with a linear unit LV-50 and T8000 controller, Hommelwerke GmbH, Germany) (Figure 17).

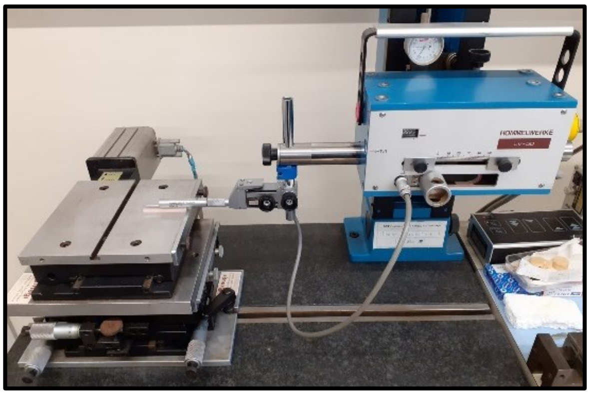

Figure 17. *Hommelwerke with a linear unit LV-50 and T8000 controller*

The surface of the specimen was transversed by a diamond tip with a constant load along a straight measuring length of 4.8 mm with a speed of 0.5 mm/s. The TK300 pick-up with a vertical range of measurement of ± 300 µm, a tip radius of 5 µm and a cone angle of 90º was utilized for the procedure.

Surface roughness parameters and profilometric profiles were extracted. Initially, a primary profile (Profile P) was obtained with an unfiltered length lt (Table 5). Subsequently, a Gaussian filter was applied to the Profile P, resulting in a roughness profile (Profile R) with a length lm (Figure 2).

The Gaussian filter with a cut-off length (λc) was selected based on the expected roughness threshold for microbial colonization (Ra = 0.2 µm), in accordance with ISO 4288:1997 (54). The transverse length was directly determined by the chosen cut-off length (λc = 0.8 mm) (Table 15).

__Table 15.__ Selected cut-off and transverse lengths (ISO 4288: 1997)

Cut-Off (λc) mm	Transversing Length (lt) mm
0.8	4.8

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*)

4.2.3. Surface roughness parameters

4.2.3.1. Arithmetic mean height

The most common parameter to evaluate surface roughness is arithmetic mean roughness (Ra) (46, 47, 50). It results to filtered profile (lm) through a cut-off wavelength (λc). The arithmetic mean height (Pa) is referent to the primary unfiltered profile (lt) (47). The mathematical formulation is previously described in Table 6.

The unfiltered profile extends to a measuring length (lt) of 4800 µm. The filtered profile corresponds to a measuring length (lm) of 4000 µm. The difference between these measuring lengths (Figure 18) represents the selected cut-off length (λc) (Table 15).

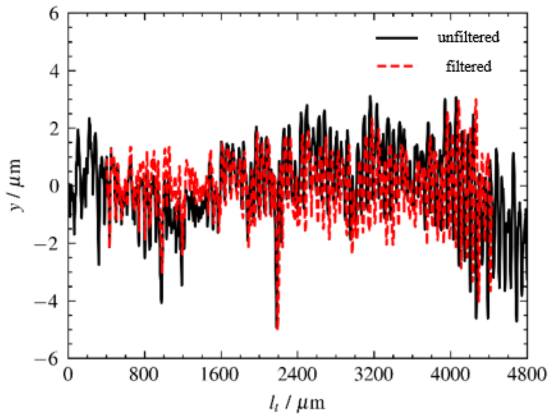

***Figure 18.** Roughness profile (y/lt)*

*Figure published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*).

4.2.3.2.Skewness (Rsk) and Kurtosis (Rku)

The same Ra value is described in surfaces with varying shapes (46). Skewness and kurtosis should be considered to provide perspectives into the distribution of heights across the surface (46, 68).

The authors suggest the following method for assessing surface roughness in dental acrylic resins: Pa (arithmetic mean height), Psk (skewness) and Pku (kurtosis).

4.2.4. Statistical analysis

The results obtained from the evaluation of surface roughness parameters were subjected to both descriptive and inferential statistical analysis using IBM® SPSS® for Macintosh, version 25 (IBM Corporation, USA) with significance level α set a 0.05.

Pa and Ra roughness values were represented using the mean and standard deviation with a 95% confidence interval for the mean. A descriptive analysis was implemented to summarize skewness (Rsk/Psk) and kurtosis (Rku/Pku). High kurtosis values indicate a sharp amplitude distribution with large peaks and valleys. A negative skewness suggests a concentration of the material near the top of the profile and a plateau-like surface. In addition, the variation coefficient (CV) (ratio between standard deviation and average value) was utilized.

A two-way analysis of variance (ANOVA) with Bonferroni correction and the Games-Howell post-hoc test was employed to:

- Compare the distribution of surface arithmetic mean height (Pa) and arithmetic mean roughness (Ra) between the different polishing techniques and between resin types.
- Compare the distribution of surface arithmetic mean roughness (Pa) between different resin types.

In order to test the means between CAD/CAM and conventional techniques to obtain acrylic resins, Student's t test was employed to assess differences in the distribution of Pa between pairs of resins.

Non-parametric tests (Mann-Whitney U and Kruskal-Wallis (H)) were selected to compare differences between groups. Pairwise comparisons were conducted using the Mann-Whitney U test to compare Pa values across different resin types within each polishing technique. The Kruskal-Wallis (H) test was utilized to assess the significance of disparities in mean Pa values between mechanized polishing, conventional polishing, and the control group.

5. RESULTS

The study compromised two groups, each containing of five distinct types of acrylic resins. In one group, the samples underwent mechanical polishing, while in the other, manual polishing was performed. Each resin was compared to a counterpart of the same type that did not undergo the polishing protocol, serving as the control in the experimental study.

5.1. SURFACE ROUGHNESS PARAMETERS: A DIFFERENT APPROACH

Table 16 represents the mean roughness parameters measured for different polishing techniques. Pa values represent the unfiltered groups and Ra values corresponds to filtered group.

Table 16. *Dispersion measures of roughness for different polishing techniques.*

Measure	Sample			ANOVA	
	Mechanized	Manual	Control	F	*p*-Value
Pa (µm), mean ± SD	1.49 ± 0.50	1.49 ± 0.50	11.11 ± 4.18	90.139	<0.001
Ra (µm), mean ± SD	0.89 ± 0.32 *	0.52 ± 0.17 *	2.13 ± 0.14 *	53.028	<0.001

* significant differences between groups on post-hoc analysis; F, ANOVA F-statistic.

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach To Analyzing The Surface Roughness Of Prosthetic Dental Acrylic Resins. App. Sci. 2024 Jan;14(2): 619*).

In terms of Pa, the mechanized technique demonstrated the lowest mean value at 1.49 µm, followed closely by the manual technique at 1.49 µm. The control group exhibited the highest mean value at 11.11 µm (Table 15). The ANOVA F-statistic of 90.139, along with the associated *p*-value of <0.001, underscores a statistically significant difference in Pa distribution among the three groups. However, the lack of homogeneity among variances between the samples precluded the identification of significant differences in the post-hoc analysis, as revealed by the Games–Howell test.

Similarly, for Ra, the mechanized technique displayed the lowest mean value at 0.89 µm, followed by the manual technique at 0.52 µm, and the control group at 2.13 µm. The ANOVA F-statistic of 53.028, coupled with a *p*-value of <0.001, indicates a statistically significant difference in the Ra distribution among the three groups. Post hoc analysis further corroborated noteworthy differences in Ra between all three groups, with both the mechanized and manual techniques surpassing the control in performance.

The coefficient of variation (CV) for Pa displayed relatively similar values across the three groups, ranging from 0.334 for mechanized to 0.377 for control (Table 17). By contrast, the CV for Ra exhibited a distinct pattern, with the control group registering a lower value of 0.067 compared to 0.362 for mechanized and 0.323 for manual.

Table 17. *Coefficient of variation (CV) for different polishing techniques*

Coefficient of Variation (CV)	**Sample**		
	Mechanized	**Manual**	**Control**
Pa (µm)	0.334	0.337	0.377
Ra (µm)	0.362	0.323	0.067

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*).

Surface roughness parameters, skewness and kurtosis (Table 18), were submitted to a descriptive analysis.

Table 18. *Skewness and kurtosis*

	Unfiltered	**Filtered**
Skewness	Psk	Rsk
Kurtosis	Pku	Rku

Table 19 and 20 exhibit filtered and unfiltered data for skewness and kurtosis for the different groups, respectively.

Table 19. *Skewness data for two groups of specimens.*

Statistics	**Psk**	**Rsk**
Control	−0.452	−0.282
Mechanized	−0.893	−1.153
Manual	−0.416	−1.365

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*).

Table 20. *Kurtosis data for two groups of specimens.*

Statistics	**Pku**	**Rku**
Control	0.461	−0.032
Mechanized	3.348	4.921
Manual	0.819	8.267

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*).

The skewness values indicate a leftward tendency for the three categories, aligning with the text's observation of heightened skewness heterogeneity in this category. The mechanized and manual categories exhibit a larger magnitude value compared to the control. A more pronounced distribution with lower values is found in the manual category (Table 19).

The kurtosis values indicate a platykurtic distribution (Pku/Rku < 3) for the control category. After the polishing procedures (mechanized and manual), the probability of occurrence of extreme values increased with a distribution tendency for leptokurtic (Pku/Pku > 3). On the other hand, a platykurtic distribution (Pku = 0.819) is found on the profile of kurtosis for manually polished samples (Table 20).

Figure 19 represents the height distribution curve for the filtered and unfiltered profiles: control (A, B), mechanically polished (1A, 1B), and manually polished (2A, 2B).

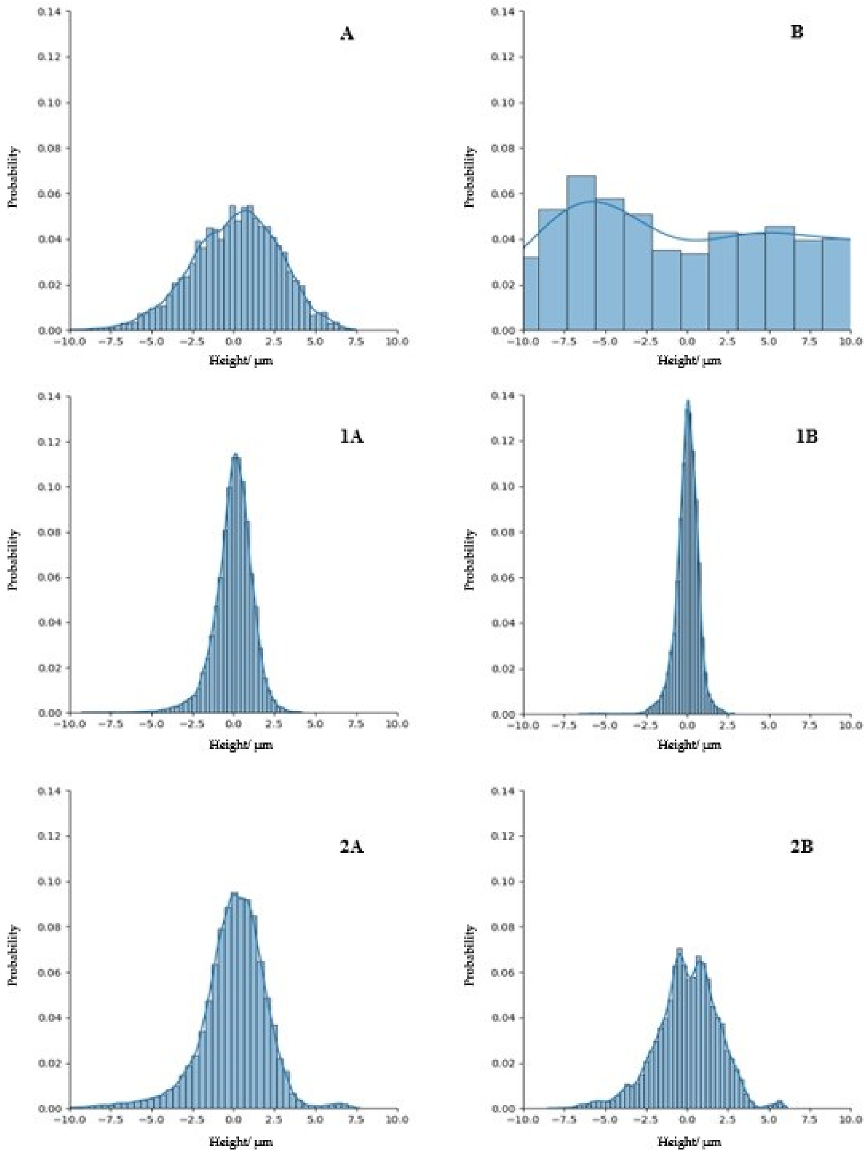

Figure 19. Height distribution curve

Subtitle: filtered profiles ((A) Control sample; (1A) Mechanized polished samples; (2A) Manually polished samples); unfiltered profiles ((B) Control sample; (1B) Mechanized polished samples; (2B) Manually polished samples).

*Image published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. Applied Sciences. 2024;14(2):619*).

5.2. SURFACE ROUGHNESS DETERMINANTS

Surface roughness determinants were analysed through arithmetic mean height (Pa), skewness (Pku) and kurtosis (Pku). Only the parameters extrapolated from the unfiltered profile were considered.

5.2.1. Inherent characteristics of acrylic resins

Table 21 compares roughness data for different processing techniques and resin types. The overall mean roughness (Pa) for conventional techniques is 11.35±4.68 µm, significantly higher than CAD/CAM techniques at 2.26±1.29 µm (t=4.595; *P*<0.001), indicating that CAD/CAM yields lower overall Pa. Among resin types, heat-cured resins stand out with the highest mean Pa at 14.10±4.80 µm, showing significant differences in inter-group comparison statistics (F=6.975; *P*=0.06). Post-hoc tests highlight significant differences, with heat-cured resins differing from 3D printed (*P*=0.034) and milled resins (*P*=0.015).

Table 21. *Roughness data for different processing methods and resin types.*

Overall Pa (µm), mean±SD					**Inter-group comparison statistics**
Conventional		**CAD/CAM**			
11.35±4.68		2.26±1.29			t=4.595; *P*<0.001
Resin-specific Pa (µm), mean±SD					**Inter-group comparison statistics**
Self-cured	**Injected molded**	**Heat-cured**	**3D printed**	**Milled**	
11.77±5.26	8.19±3.20	14.10±4.80[a,b]	3.00±1.48[b]	1.51±0.56[a]	F= 6.975; *P*=0.06

a,b: significant differences in pairs of resins using Bonferroni post-hoc correction at *P*<0.05.

*Table published on Paper 2 (67) (*Quezada MM, Fernandes CMdCG, Martín JM, Correia ARM, da Fonseca PAB. Influence of different processing techniques for prosthetic acrylic resins in the surface roughness parameters: a research article. BMC Oral Health. 2024;24(1):641*)

Table 22 provides an analysis to the surface roughness measurements for dental acrylic resins and the corresponding processing techniques.

Table 22. *Measures of roughness dispersion for polishing techniques and resin types.*

Resin types and polishing techniques	Variation coefficient (CV)	Skewness (Psk)	Kurtosis (Pku)
Conventional			
Self-cured	0.447	-0.453	0.462
Injected molded	0.391	0.872	1.068
Heat-cured	0.341	0.339	0.267
CAD/CAM			
3D printed	0.493	0.201	1.578
Milled	0.371	-0.135	0.138

*Table published on Paper 2 (67) (*Quezada MM, Fernandes CMdCG, Martín JM, Correia ARM, da Fonseca PAB. Influence of different processing techniques for prosthetic acrylic resins in the surface roughness parameters: a research article. BMC Oral Health. 2024;24(1):641*)

The variation coefficient (CV) indicates variability in roughness. 3D printed and self-cured resins have higher CV values (3D printed: CV = 0.493, self-cured: CV = 0.447), suggesting greater variability. In contrast, heat-cured (0.341) and milled resins show lower CV values (0.371). Surface profiles also reveal distinct characteristics. Self-cured (-0.453) and milled (-0.135) resins have a plateau-like surface with negative skewness, while injected molded resins show sharp variations with positive skewness (0.872) and substantial kurtosis (1.068).

Surface profiles also reveal distinct characteristics (Figure 20).

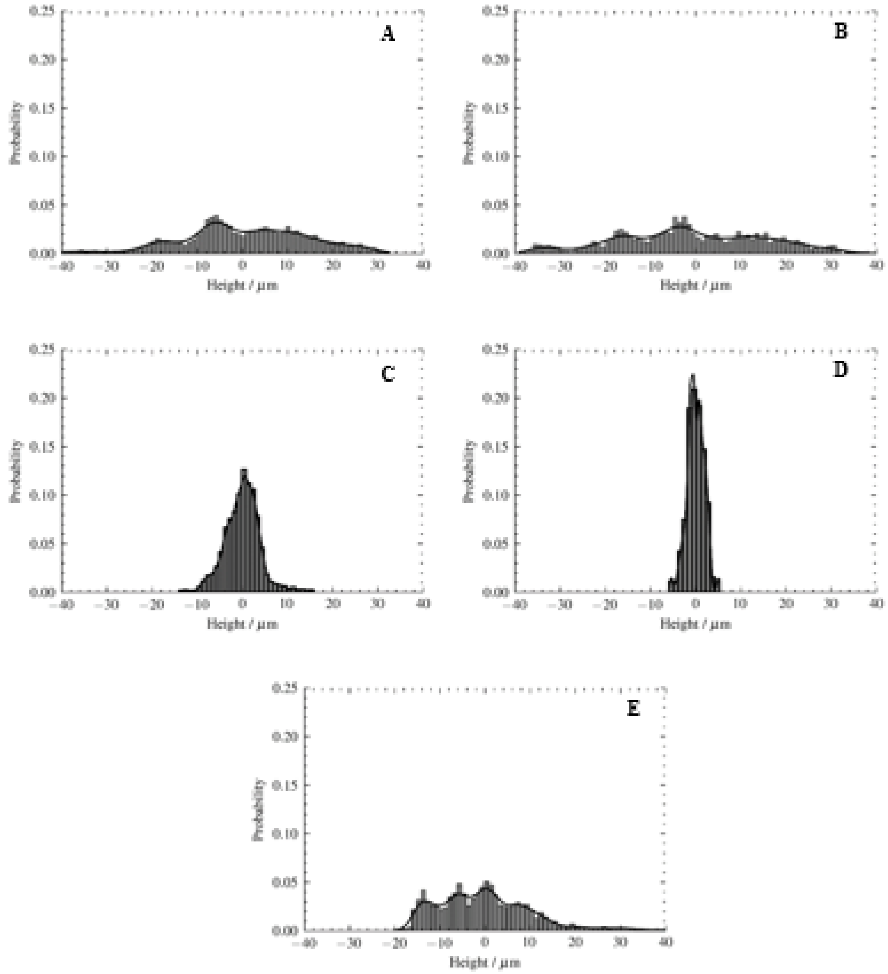

Figure 20. *Probability of having a given height of the surface for the specimens according to resin processing type*

Subtitle: A (self-cured), B (heat-cured), C (3D printed), D (milled), E (injected molded).

*Figure published on Paper 2 (67) (*Quezada MM, Fernandes CMdCG, Martín JM, Correia ARM, da Fonseca PAB. Influence of different processing techniques for prosthetic acrylic resins in the surface roughness parameters: a research article. BMC Oral Health. 2024;24(1):641)*

5.2.2. Polishing protocols

Table 23 illustrates the mean Pa values for the study group (mechanized polishing (6.04±5.45 µm) and conventional polishing (4.27±4.74 µm)), and for the control group (7.72±5.86 µm), revealing a significant difference (p=0.003, Kruskal-Wallis test). While mechanized polishing yields higher roughness compared to conventional polishing and the control group, both mean Pa values obtained from mechanized and conventional polishing are significantly lower than those of the control group (Figure 21).

Table 23. *Roughness data for polishing techniques and resin types (Pa/µm).*

Mechanized polishing	Conventional polishing	Control	P-value
6.04±5.45	4.27±4.74	7.72±5.86	0.003

Significant disparities emerged in the overall Pa values between mechanized and conventional polishing techniques, with mechanized polishing notably yielding higher roughness compared to the control group (6.04±5.45 µm vs. 4.27±4.74 µm; p=0.004) (Figure 21). Notably, Pa values exhibited variations across different resin types, with self-cured and injected molded resins generally manifesting higher values, while 3D printed and milled resins demonstrated lower values.

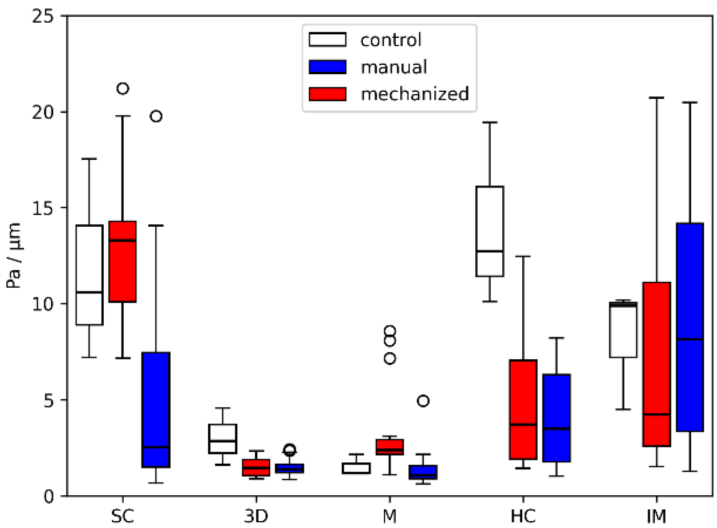

Figure 21. *Distribution and dispersion of Pa (µm) with control group*

Subtitle: SC – Self-cured, 3D – 3D printed, M – Milled, HC – Heat-cured, IM – Injected molded

Specifically, self-cured (p<0.001) and milled (p=0.001) mechanized polished resins demonstrated significantly higher Pa values compared to conventionally polished resins. However, no significant differences in irregularity Pa values were discerned in the subgroup analysis for 3D printed, injected molded and heat-cured resins (Table 24).

Table 24. Roughness data for polishing techniques and resin types

Polishing technique	Overall Pa (µm), mean±SD	Resin-specific Pa (µm), mean±SD				
		Self-cured	**3D printed**	**Milled**	**Injected molded**	**Heat-cured**
Mechanized	6.04±5.45	13.12 ± 4.00	1.49 ± 0.50	3.32 ± 2.47	7.17 ± 5.95	5.11 ± 3.61
Conventional	4.27±4.74	5.46 ± 5.51	1.49 ± 0.50	1.44 ± 1.08	8.93 ± 6.23	4.01 ± 2.58
U statistics	2051.500	28.500	111.000	29.000	223	93.000
P-value	0.004	<0.001	0.950	0.001	0.443	0.419

The analysis of roughness dispersion across various polishing techniques and resin types is presented in Table 25 and Figure 21.

Mechanized polishing demonstrates relatively consistent skewness values across resin types, ranging from 0.51 to 1.49, suggesting a moderate concentration of material near the top of the profile and a plateau-like surface. However, conventional polishing exhibits greater variability in skewness, with values ranging from 0.41 to 2.75.

Particularly noteworthy is the conventional polished milled group, which shows significantly higher skewness (2.75), indicating a more pronounced distribution of material with a longer tail towards higher amplitudes compared to other conventional techniques.

Regarding kurtosis values, mechanized polishing techniques generally exhibit low to moderate values, ranging from -1.04 to 0.83, indicating a relatively balanced amplitude distribution with smaller peaks and valleys. In contrast, conventional polishing techniques display significantly higher kurtosis values, ranging from -1.46 to 18.92. The conventional milled group stands out with an exceptionally high kurtosis of 8.71, suggesting a sharp amplitude distribution with large peaks and valleys.

Table 25. Measures of dispersion of roughness for polishing techniques and resin types

Group	Resin type	Skewness	Kurtosis
Mechanized	Self-cured	0.51	0.07
	3D printed	0.52	-1.04
	Milled	1.49	0.83
	Injected molded	1.04	0.13
	Heat-cured	0.75	-0.62
Conventional	Self-cured	1.54	2.16
	3D printed	0.84	-0.24
	Milled	2.75	8.71
	Injected molded	0.44	-1.08
	Heat-cured	0.41	-1.46
Control	Self-cured	-0.28	-0.03
	3D printed	-0.10	2.23
	Milled	-0.85	2.04
	Injected molded	3.17	18.92
	Heat-cured	0.66	2.10

Figure 22 allows the analysis of the distribution and dispersion of roughness values. Both conventional and mechanized polishing techniques do not exhibit symmetrical distribution for any of the resin types. In terms of dispersion, conventional polishing exhibited slightly higher dispersion compared to mechanized technique, in contrast with self-cured resin, where mechanized polishing showed slightly higher variability. There is no discernible pattern indicating that one polishing technique consistently in higher dispersion across all resin types.

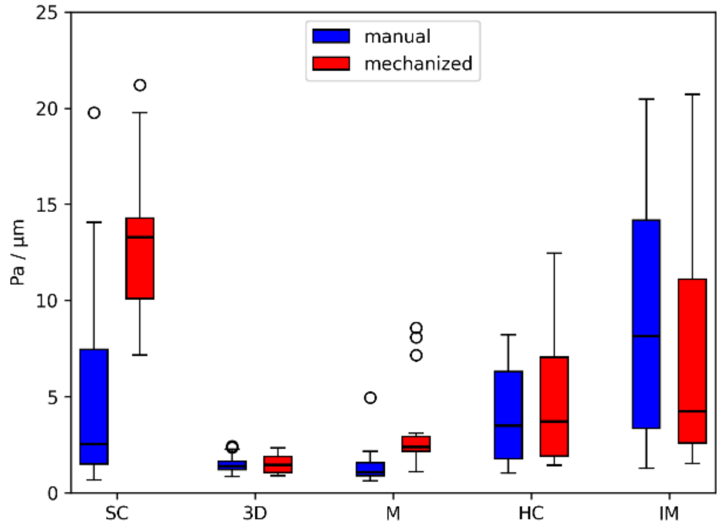

Figure 22. *Distribution and dispersion of Pa (µm) without control group*

Subtitle: SC – Self-cured, 3D – 3D printed, M – Milled, HC – Heat-cured, IM – Injected molded

6. DISCUSSION

The oral cavity presents a unique environment, imposing significant requirements on materials used in oral rehabilitation treatments. Dental materials must be adapted to the functional and biological requirements inherent to the oral cavity environment. They are directly in contact with saliva and crevicular fluid, and, consequently, are subjected to fluctuating temperatures, masticatory forces, and sustained functional stresses. Additionally, dental materials have prolonged intimate contact with oral tissues, and, as so, they must be biocompatible and non-cytotoxic (2, 4, 72).

Polymers are materials employed in various types of prosthetic rehabilitation, including removable prostheses, interim prostheses, and prostheses retained/supported by implants. PMMA formally referred to as poly (methyl methacrylate) in accordance with the IUPAC nomenclature, persists as the prevailing polymer employed in the manufacture of dental prostheses. However, this polymer has mechanical and biological disadvantages (2, 11).

The conventional approach to manufacture PMMA-based prosthetic bases relies on the operator's skills and the manufacturing process, factors that predispose the development of failures such as porosity, surface roughness and dimensional inconsistencies in the resin surface. CAD/CAM technologies have emerged to standardize the production method, reduce the manufacture time, and rectify the deficiencies inherent to the conventional approach (33, 34, 73).

Pathological processes (29), such as prosthetic stomatitis and oral candidiasis may develop due to microbial plaque accumulation on the prosthetic surface, resulting from inadequate oral hygiene, abrasive processes during chewing and mechanical cleaning, and reduced salivation often observed in elderly patients. To mitigate this accumulation, prosthetic polishing procedures are recommended, in particular, the mechanical process, given that the chemical methodology demonstrates biocompatibility problems in the interaction with the oral cavity (62). Denture base resins characterized by smooth surfaces exhibit reduced susceptibility to microbial adhesion, thereby substantially enhancing denture longevity, particularly when combined with healthy underlying tissue (62, 74).

Surface roughness is a relevant clinical factor, as it directly or indirectly, affects the retention of microbial plaque on tissues in contact with materials (28) and its characterization is performed using several parameters (46, 47, 50).

The design of the present research aimed, firstly, to validate a different approach for the analysis of surface roughness height parameters by pre-emptively identifying the limitations (46, 47, 50) related with their analysis (Paper 1). Secondly, it is recognized that it can be influenced by the skill of the operator, the polishing protocol and the material's composition itself (41, 75). To ensure consistency and minimize the influence of variables, a single operator conducted both polishing methods. The polishing rate (rotations per minute) and duration were uniformed. Based on the approved evaluation methodology, the "*in vitro*" study proceeded to the evaluation of the influence of the inherent characteristics of acrylic resins (Paper 2) and the polishing protocols (mechanized and conventional) on the surface roughness parameters.

Although, the *"in vitro"* design, in accordance with what is described in the literature, the acrylic resin samples were immersed in distilled water at a constant temperature of 37º C to simulate the rehydration conditions of the denture base in the oral cavity environment. It is expected to be crucial for effectively reducing residual monomer content (2, 76). The presence of residual monomer MMA in the acrylic resins of prosthetic bases is the result of incomplete resin polymerization (76) that directly influence properties such as dimensional stability, tensile, flexural strength, surface roughness and biocompatibility. The reduction of residual monomer is desirable to ensure proper interaction of the prosthetic base with the oral cavity (2).

6.1. SURFACE ROUGHNESS OF ACRYLIC RESINS

Surface roughness is a variable used to describe the quality of a surface (77). A direct correlation can be stablished with plaque accumulation, discoloration, material degradation and patient dissatisfaction (78, 79).

6.1.1. Evaluation parameters

Per definition, surface roughness is referent to the variation in the height of the surface relative to a reference plane (50). The roughness of a surface is determined by the micro-geometry of its components. Defining this micro-geometry involves utilizing a range of quantities, which are determined through contact-type measurements based on the identified surface profile (44, 45, 50).

The surface roughness and its quantities are characterized by a high degree of variability. Ensuring consistent and uniform roughness characteristics throughout the entire surface proves to be difficult (45).

The selection of the most suitable and relevant roughness parameters to monitor the desired surface properties remains a challenge. The need to promptly identify a subset of parameters that correlate with surface functionality has been underscored (68).

The prevalent metric used for assessing surface roughness is Ra (the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation and length). Ra offers a general overview of height variations; however, it lacks into surface shape, frequency and regularity of these variations (39, 41, 46, 80). Additionally, Ra does not provide information about specific wavelengths and is not responsive to minor changes in the profile. It exclusively focuses on the vertical deviation of the profile, neglecting to provide insights into the slopes, shapes, sizes of asperities or the frequency and regularity of occurrence (46). Surface defects have a minimal impact on the recorded outcomes. Consequently, the measure of Ra will present more repeatability than a measuring parameter sensitive to individual peaks and valleys (40) and an identical Ra value can be presented for different surfaces (40, 46).

The authors of this research advocate the incorporation of the primary profile (P) to surface analysis. The primary profile is crucial to the evaluation of surface roughness as it directly represents surface details, including peaks and valleys and all height variations (46, 47, 50). Arithmetic mean height (Pa) is the representation of the average unfiltered peak and valley distances from the mean surface profile, and, can be considered an extension of the Ra to the profile (39). The discrepancies observed are comparable to the Ra values obtained from the filtering operation, which effectively removes the most profound irregularities on the surface (40). Significant differences were found in three groups ($p<0.01$) for Ra; however, the heterogeneity among samples for Pa makes it difficult to determine these significant differences.

Table 26 was developed for Paper 1 and analyses the differences presented between both parameters.

Table 26. Comparison between arithmetic mean roughness (Ra) and arithmetic mean height (Pa)

Ra:	Pa:
• Result of a filtering operation that excludes information from a surface;	• Direct extraction of the primary profile.
• Only addresses surface irregularities in a vertical direction; • Height average deviation to the mean line (does not differentiate peaks and valleys); • Same Ra value with different tribological performances.	**Skewness and Kurtosis** • Height distribution and tip geometry of peaks and valleys; • Describes how the roughness is distributed along the profile; • Differentiates between different tribological performances.

*Table published on Paper 1 (53) (*Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach To Analyzing The Surface Roughness Of Prosthetic Dental Acrylic Resins. App. Sci. 2024 Jan;14(2): 619*).

Specific height parameters, as skewness and kurtosis should be considered to distinguish surfaces of varying shapes with the same Pa value (46) and to supply insights regarding the distribution of heights across the surface (46, 68).

The height distribution is represented by the height probability density, comparing the probability of a given surface height relative to the centreline for each group. Corsalini et. al (39, 40) evidenced a quasi-normal Gaussian distribution for mechanized polished specimens and a clearly asymmetric distribution for manually polished specimens. In contrast, in the present research, after the polishing procedure (manual or mechanized), the present authors verified that the height distribution displayed an increase in kurtosis and a leftward skewness tendency, signifying asymmetry in height data and extreme values associated with valleys. Negative skewness describes a significant number of local maxima below the mean, as compared to a Gaussian distribution (46, 50, 81), which corresponds to areas with deep valleys and a lack of high peaks. A parameter Pku >3 (leptokurtic) describes surfaces with high peaks and deep valleys. By combining both parameters, a plateau-like smooth surface with deep valleys is observed, similar to the mechanized samples.

Gaussian and non-gaussian distribution directly affect different tribological behaviours (82). Literature describes skewness and kurtosis intricately related to the functionality of surface materials (56, 60, 68).

For example, the shear bond strength of prosthetic rehabilitations in zirconia ceramics was evaluated with these parameters (83). These are critical for clinical assessment of retention and fit, fatigue life, resistance, tissue response, aesthetics, cleaning and maintenance of denture base acrylic resins (46, 69).

6.1.2. Surface roughness determinants

6.1.2.1. Inherent characteristics of acrylic resins

The literature also describes that surface height distribution features are contingent on the processing method used (70). An extensive analysis of the influence of resin processing techniques on surface roughness height parameters was performed. The validation of using arithmetic mean height (Pa) instead of arithmetic mean roughness (Ra) has already been confirmed (39, 40) and discussed in the last item 6.1.1.

The composition between the conventional PMMA and CAD/CAM PMMA is similar and described in several studies (2, 32). However, their processing technique is entirely different (84), and it can affect surface roughness.

In terms of surface roughness, when compared the conventional and CAD/CAM processing techniques, a notable distinction in mean Pa ($t=4.595$; $p<0.001$) is presented. Specifically, in pairwise analysis, heat-cured resin revealed significant differences from both 3D printed ($p=0.0034$) and milled resins ($p=0.015$). The prefabricated and the layer-by-layer PMMA demonstrate enhanced surface properties relative to the heat-cured resin, primarily attributed to reduce pressure, temperature conditions and levels of residual monomers (26, 85).

Heat cured resins revealed the highest values of Pa in contrast with the values obtained by Berger et al. (76). The initiation of the polymerization reaction is triggered by heat, leading to the expectation of nearly complete conversion of the MMA monomer. Furthermore, the resultant polymer exhibits a reduced granule size in contrast to self-cured resins. The selection of reaction initiators (e.g. benzoyl peroxide and 1,4-butanediol dimethacrylate) can also exert a direct impact on surface roughness (33, 34).

An analysis to the overall roughness level appears to be a critical factor associated to surface characteristics. Literature (56, 68, 82, 86) describes the potential to evaluate the surface texture consistency. Density and distribution probability curves are established based on the processing method's characteristics (Figure 20).

In this research, concerning surface roughness (Pa), the coefficient of variation (CV) represents an indicator of dispersion relative to mean values. The findings of the CV indicate reduced variability in overall Pa for milled (CV = 0.371) and heat-cured resins (CV = 0.341), suggesting a higher probability density and less dispersion of Pa values in their distribution curve. In contrast, self-cured resins (CV = 0.447) and 3D printed resins (CV = 0.899) exhibit higher CV values, indicating greater heterogeneity in surface texture. In accordance with the results acquired, Alharethi (27) described that the tools of milling machines carefully remove material in layers until the desired shape is achieved. The contact of the drill with the surface is continuous and yield to more consistent and smoother surfaces compared to 3D printing. The 3D printing process can contribute to surface roughness development by the formation of partially cured particles, particularly if sufficient post-curing is not carried out. These particles have the potential to dislodge and create small pores (27, 87). Another issue described in the 3D printing process is step like structured surface generated in the layer-by-layer configuration. The 45-degree orientation creates oblique ridges which are associated to rougher and heterogeneous surfaces (88).

The characterization of non-Gaussian topographies involves the assessment of skewness and kurtosis of the height distribution (82). A non-Gaussian distribution of roughness profile is characterized by Psk and is responsive to sporadic deep valleys and high peaks, as it quantifies the symmetry of the profile distribution in relation to its central line (46, 50). Processes like grinding and milling are described to produce negatively skewed surfaces (82). Profiles with negative skewness are predominantly found in deep valleys, as evidenced in self-cured (Psk = -0.453) and milled (Psk = -0.135) resins. Additionally, non-gaussian surfaces characterized by relative flat peaks and valleys are identified by Pku value less than 3, which is consistent across all types of resins. In contrast, injected molded resins display sharp variation with positive skewness (0.872) and significant kurtosis (1.068). The elevated Pku value suggests the presence of extreme peaks and valleys on the surface (56). Similar to the results obtained, Gungor et al. (63) found significant differences ($p<0.001$) in surface roughness mean values for injected molded resins. The pressure exerted during polymerization process can result in shrinkage which can manifest on the material's surface (89). Due to its chemical structure, the injected molded resin is composed of long chains with a few cross-linkers between them, resulting in low hardness and reduced abrasion (73, 90). Also, during profilometric reading, the displacement of the tip on the surface can generate secondary roughness, as the hardness it exceeds that of the resin (44).

6.1.2.2.Polishing protocols

Effective biofilm control is crucial to extend the durability of denture base materials to optimize patient's oral health. A rough surface is susceptible to discoloration or pigmentations, increasing bacterial accumulation and may promote abrasion wear of opposing dental elements (69).

The selection of a proper polishing procedure is essential to enhance aesthetics, reduce bacterial plaque accumulation and improve the resistance to oral fluids. Therefore, the knowledge of surface topography, hardness and abrasion of materials intended for use in the oral cavity is imperative (91-93).

Polishing protocols exert a considerable influence on the surface roughness of denture base materials by aiming for the gradual removal of rough layers from the surface (75). Statistically, the outcome of a polishing procedure is intended to flatten the surface peaks, resulting in a height data distribution with numerous high points of similar heights (81). From a clinical perspective, the polishing procedure is an abrasion process that involves traversing a series of abrasive particles (varying in fineness) across the surface. Its effectiveness might be affected by factors such as the pressure applied by the abrasives, along with their shape, size, rate and duration of movement (77, 94).

As previous described, intrinsic factors like polymerization temperature, pressure and PMMA composition directly impact surface topography, thus determining the appropriate polishing procedure to be applied. The importance of selecting and using suitable abrasive tools was described by Linke et. al (68). Variation in abrasive grain sizes and distribution can modify surface roughness and impact functionality (68, 77). Inadequate polishing protocols have been associated to secondary roughness.

A challenge related to polishing protocols is their reliance on variables influenced by the operator (39-41). Corsalini et al. (39) established the first standardized technique for polishing acrylic resins with the goal of ensuring consistent repeatability and simplifying the comparative assessment of different resins. Researchers have proven the efficacy of a mechanized polishing protocol, revealing significant differences between the control group and the study samples (39, 40), consistent with finding obtained in our research (p=0.003) (Figure 22). Subsequently, in 2022 (41), it was developed a chairside mechanized tool to replicate the same procedure, named control polishing tool (CPT). The proof-of-concept of the CPT protocol proved its efficacy with the test samples of 3D printed resin with lower values of surface roughness (p=0.04) in relation to the control (without polishing protocol) (66).

In the present research, the Pa values of the CPT protocol proved to be higher compared to the conventional method (6.04±5.45 µm vs 4.27±4.74 µm). Therefore, despite its proven efficacy, the conventional polishing remains remarkable, in contrast with the results obtained by the mechanized method developed by Corsalini et al. (40). Considering the resemblance in polishing conditions between both protocols (41, 66), it can be inferred that calibration of the CPT protocol is necessary. The pressure exerted by the handpiece on the samples is the only varying factor. On the conventional protocol, the pressure is manually applied; however, the CPT protocol involves the movement of the handpiece on a platform, potentially affecting the pressure exerted to achieve the desired level of polishing (41). Nevertheless, despite the fact that originally the average Ra levels for each technique exceeded the 0.2 µm threshold for plaque accumulation (28), almost all the resins remained below the clinically acceptable value of 10µm (26, 95), except the self-cured mechanized polished group (13.12 ± 4.00 µm).

The initial research investigated the efficacy of CPT protocol; however, its primary aim remains to achieve consistent and uniform polishing compared to the conventional protocol (reliant on human intervention). Roughness parameters related to amplitude, skewness (Psk) and kurtosis (Pku) were evaluated to provide a more comprehensive characterization into the shape and characteristics of the distribution of the roughness values after the polishing procedure. A combined analysis of the box plots (Figure 21 and 22) with the statistical measures of skewness and kurtosis was developed. The box plot is a graphical representation that summarizes a dataset's distribution (96) allowing to compare, in this particular research, the effectiveness of polishing method and to assess the distribution of roughness data.

The length of the boxplots is representative of data spread. Varying lengths are evident (Figure 21 e 22), therefore, a symmetrical distribution and consistent pattern for Pa values were not observed across resin types and polishing techniques.

The conventional method produced a broader range of roughness across resin types, particularly for self-cured and injected molded, identified as outliers, and potentially considered infrequent occurrences (Figure 21 e 22). Although, mechanized polishing, produced higher roughness values for self-cured and injection-molded surfaces, it achieved consistent roughness for the other resins (3D printed, milled and heat-cured). This consistency is reflected in the narrower interquartile ranges. Data from mechanized polishing exhibited significantly lower dispersion, primarily because the protocol's effectiveness being independent of human factors (39, 40).

3D printed and milled surfaces in both polishing methods achieved lower roughness values, suggesting that these resins are responsive to both manual and mechanized polishing. Self-cured mechanized polished (13.12 ± 4.00 µm) and injection-molded conventionally polished (8.93 ± 6.23 µm) resins exhibited higher roughness, indicating that theses surfaces might be more susceptible to irregularities introduced during the polishing process. A single operator executed the same polishing protocol.

The box plot presented more outliers for conventional polishing which reflects more irregularities and inconsistencies compared to conventional polishing, primarily because the protocol's effectiveness being susceptible to human factors (39, 40). Although, a relevant outlier can be detected on the group of mechanized polishing for milled resins, the higher degree of polymerization could be the explanation for the increased surface pressure resistance and the appearance of secondary roughness (32, 34).

After a polishing procedure, it is expected that the surface displays a distribution with negative skewness, with data more concentrated around the mean compared to the original surface data. The negative skewness indicates that the polishing process leads to a higher frequency of data points along the newly generated surfaces resulting from the removal of peaks (81, 97). Both polishing protocols contributed to the increase of skewness and kurtosis values across all resin types, which suggests that the chosen polishing kit used is more likely to develop additional surface peaks and its inefficiency to remove them (98, 99).

Mechanized polishing generally resulted in a positively skewed distribution, indicating a concentration of lower roughness values, but with some higher roughness points (extreme values). The distribution tends to have lower kurtosis suggesting flatter peaks and moderate tails, reflecting the more consistent roughness observed in the box plots, except for the milled resins. On the other hand, conventional polishing exhibited more variability and higher skewness and kurtosis for several resin types, indicating more variability and extreme values, which aligns with the wider spread and more outliers seen in the box plots and tends to produce broader distribution of roughness values, reflecting higher irregularities compared to mechanized polishing. The hypothesis proposed by Corsalini et. al (40) that mechanized protocol would result in more consistent surfaces was substantiated.

The integration of this data to analysis lead to a deeper understanding of the distribution characteristics of roughness across different polishing methods and resin types. This analysis underscored the importance of selecting the appropriate polishing method based on the specific surface characteristics and desired outcomes, which should be mandatory for the companies when selling these products for dental laboratories/ dental clinics.

6.2. FURTHER INVESTIGATION

Surfaces with the same roughness height but different surface skewness could lead to great difference in tribological properties (82, 100). The functionality of a surface is intricately related to its finish, including both texture and mechanical properties of the surface layer. These are subjected to daily use and consequent wear within the oral cavity. Similar observations have been made in studies with other materials (56, 60, 68).

Skewness and kurtosis are stablished to be critical parameters for the clinical evaluation of various aspects concerning denture base acrylic resins. Further investigation should include retention and fit, fatigue life, corrosion resistance, wear resistance, tissue response, aesthetics, cleaning and maintenance. For example, Sedlaček et al. (80) investigated the impact of initial surface roughness on the tribological behaviour during pin-on disc tests. The disc surface was subjected to polishing and grinding to achieve similar Ra value, but different Rsk and Rku values. Surfaces characterized by high kurtosis and negative skewness demonstrated a decrease in the friction coefficient, providing more sites for the storage of wear particles and lubricant.

A study considering the susceptibility to microbial contamination, or the accumulation of fluid/debris, should be conducted. Research findings indicate that microorganisms tend to prefer adhering to surface featuring scratches and grooves rather than those with higher Pa values (59). Literature describes that nanostructured surfaces, distinguished by their skewness and kurtosis, display a higher ration of peaks to valleys, enhancing resistance to *Candida albicans* attachment. These surfaces represent external stressors. Conversely, surfaces with valley-like nano-architecture were conductive to *Candida albicans* attachment and proliferation (30). Recognizing surface topography will facilitate the identification of surface types that are more conductive to microorganisms proliferation, such as *Candida albicans*, which is the primary cause of denture-related stomatitis (28, 30).

Furthermore, the CAD/CAM process of the CPT need to be reprogrammed. The three-dimensionality of the prosthetic bases must be considered for analysis. The challenge could be addressed by employing a high-precision robotic arm equipped with the milling tool, previously executed by Corsalini et al. (39, 40), or to attach a pulley system to the base of the prototype, allowing the milling tool to follow the curvature of the surface.

Finally, the evaluation of 3D surface topography provides a more comprehensive and detailed description of surface topography. For example, the atomic force microscopy (AFM) provides a thorough analysis of surface roughness topography, offering three-dimensional surface analysis at nanometre resolution.

6.3. LIMITATIONS

Several limitations were identified during the development of the present research. First, the proper *"in vitro"* design of the study. Given that the experimental conditions do not clinically replicate the actual conditions within the oral cavity, the results presented are limited to experimental validation only.

One of the main properties related to poly (methyl methacrylate)-based denture base is its low hardness. The surfaces are daily exposed to wear, which generates continuous changes on the roughness over time. Continuous polishing is required to ensure their durability. Das et al. (68) highlights the importance of selecting correctly abrasive grain sizes, as they have a direct impact on surface roughness and functionality, including susceptibility to microbial contamination or accumulation of fluid/debris.

The control-polishing tool (CPT) was designed to reduce the influence of operator skill. However, it introduced additional sources of variability, including the type of milling machined used, the rotation speed, the type and dimensions of the polishing tool. Nevertheless, these aspects are more controllable that the variability introduced by human factors. In addition, a potential barrier to the clinical application of the proposed mechanized system is the tridimensional shape of a denture base. A CPT is limited to perform polishing in the transverse direction only. However, it could be developed, in the near future, a polishing system with pressure control (similar to electric toothbrush) associate to the torque control of the handpiece with the aim to reduce the variability reported in our research.

Concerning the hardware to measure surface roughness, the stylus-type profilometer is commonly employed. However, it has the potential to damage the object under examination due to direct contact of the diamond stylus with the surface. Furthermore, the dimensions of the diamond stylus (ranging from 4 to 20 µm in diameter) can constrain its ability to precisely measure micro-irregularities and may not accurately represent certain surface features (44).

7. CONCLUSIONS

Regardless the limitation presented by the present *"in vitro"* research, according to the adopted methodology, it is possible to conclude:

1. **1.** The primary profile (P) is crucial to the evaluation and characterization of surface roughness. Skewness (Psk) and kurtosis (Pku) provides insights into the surface's morphology and differentiate diverse tribological behaviours.
2. **2.** The height distribution curve (Psk and Pku) describes the surface topography of manufacturing procedures. CAD/CAM resins demonstrated lower surface roughness values (Pa). Heat-cured resin exhibited better surface consistency.
3. **3.** Polishing protocols present a direct effect on the surface topography of acrylic resins. Mechanized protocol ensures consistent skewness and kurtosis values. Conventional protocol exhibited significant variations in the Pa values obtained.

8. CONCLUSIONES

A pesar de las limitaciones presentadas por la presente investigación *"in vitro"*, según la metodología adoptada, es posible concluir lo siguiente:

1. El perfil primario (P) es crucial para la evaluación y caracterización de la rugosidade de la superficie. La asimetría (Psk) y la curtosis (Pku) proporcionan información sobre la morfología de la superficie y diferencian diversos comportamientos tribológicos.

2. La curva de distribución de alturas (Psk y Pku) describe la topografía de la superficie de los procedimientos de fabricación. Las resinas CAD/CAM demostraron valores de rugosidad superficial más bajos (Pa). La resina termopolimerizable exhibió una mejor consistencia superficial.

3. Los protocolos de pulido presentan un efecto directo en la topografía de la superficie de las resinas acrílicas. El protocolo mecanizado garantiza valores consistentes de asimetría y curtosis. El protocolo convencional exhibió variaciones significativas en los valores de Pa obtenidos.

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10. APPENDICES

10.1. APPENDIX I. ORIGINAL ARTICLES QUALITY RATINGS (JCR 2022)

10.1.1. PAPER 1

Quezada MM, Fernandes C, Montero J, Correia A, Salgado H, Fonseca P. A Different Approach To Analyzing The Surface Roughness Of Prosthetic Dental Acrylic Resins. ***App. Sci.*** **2024 Jan;14(2): 619**

ISSN: 2076-3417

Impact factor: 2.7 JCR Science Edition: 2022.

Category: Engineering, Multidisciplinary

Position in the category: Q2

applied sciences

MDPI

Article

A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins

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Abstract: (1) Introduction: Apart from the polishing method, conventional or mechanized, the arithmetic mean roughness (Ra) is the most common metric to evaluate the surface roughness of denture base acrylic resins. An overview of the constraints related to this roughness parameter is highlighted in this study. This research introduces new parameters for accessing a functional analysis of surface roughness. (2) Materials and Methods: Five samples of CAD/CAM 3D-printed acrylic resins were prepared. Two polishing techniques, manual and mechanical, were applied. Surface roughness parameters were extracted from a profilometer reading: arithmetic mean height (Ra and Pa), skewness (Rsk and Psk), and kurtosis (Rku and Pku). (3) Results: Significant differences ($p < 0.001$) were found in the Ra distribution among the study samples, in contrast with the lack of significance in Pa values. Surface roughness parameters revealed an increased coefficient of variance (CV) value due to mechanized polishing across the specimens analyzed. Skewness and kurtosis indicate a more pronounced distribution with the manual polishing technique. (4) Conclusion: This preliminary study exhibits the influence of different polishing protocols on surface roughness parameters. The primary profile, skewness, and kurtosis should be assessed for the surface characterization of acrylic resins.

Keywords: polymethyl methacrylate; 3D printed resin; prosthodontics; surface roughness; functional properties

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Citation: Quezada, M.M.; Fernandes, C.; Montero, J.; Correia, A.; Salgado, H.; Fonseca, P. A Different Approach to Analyzing the Surface Roughness of Prosthetic Dental Acrylic Resins. *Appl. Sci.* **2024**, *14*, 619. https://doi.org/10.3390/app14020619

Academic Editor: Joseph Nissan

Received: 16 December 2023
Revised: 6 January 2024
Accepted: 9 January 2024
Published: 11 January 2024

1. Introduction

Acrylic resins are used for various applications in dentistry, such as denture base materials. The most common material used for denture base is poly (methyl methacrylate) (PMMA) [1].

Among PMMA properties, surface roughness emerges as a clinically significant factor, directly or indirectly impacting microbial plaque retention in tissues in contact with the denture base. A clinical threshold, devoid of statistical relevance to microbial colonization, was established at 0.2 µm [2]. Beyond this value, the potential for pathological conditions, such as prosthetic stomatitis and oral candidiasis, rises due to microbial accumulation. To counteract this, mechanical and chemical polishing processes on the prosthetic base surface are recommended to enhance the material's biocompatibility [3–5].

The surface roughness of dental acrylic resins is mainly affected by acrylic resins' inherent features, the polishing technique, and the operator's manual skills [1,4,6]. The authors of the present study propose a mechanical device for polishing acrylic resins, regardless of the individual operator's skills. When assessing surface roughness, this variable should be excluded [1].

Different surfaces exhibit different tribological properties, with surface roughness performing a major role [7]. Functional performance is significantly correlated with surface finish, encompassing surface texture, and the mechanical characteristics of the surface [8,9]. Manipulating surface roughness affects the mechanism and structure of acrylic resins, not only from the visual aspect but also from a clinical perspective, since it extends to properties such as fatigue life, wear resistance, corrosion resistance, and micro-organism deposit formation or colonization on acrylic resins [9].

To characterize and classify different surfaces, surface roughness parameters were developed and standardized through the American National Standard Institute (ANSI) and the International Organization for Standardization (ISO) [10]. ISO 4288:1996 [11] has presented rules and procedures to assess surface texture.

In general, profilometers are the most used contact instrument for measuring surface roughness, quantifying it based on the recorded surface height. The operating principle of the device consists of a diamond tip in contact with a surface that performs a straight-line scan, where height variations are converted into electrical signals, referred to as micrometric magnitudes. The measurements obtained only represent two dimensions (2D), considering that the tip only moves vertically and horizontally along a central line [12,13]. From a graphical perspective, surface roughness corresponds to variations in height on a surface relative to a reference plane [10,14,15]. However, profile graphs do not provide the quantitative data required to estimate the functional value of a surface [14,16]. Such data can be extracted from surface profile graphs by analyzing statistical parameters. These parameters measure the vertical (amplitude), the horizontal deviations (spatial), or a combination of both amplitude and spatial aspects [12–14].

This challenge emerges from the need to select suitable surface parameters for monitoring whether the desired functional surface properties are met [17]. The most common metric to analyze surface roughness is Ra (the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation and length). Although this parameter provides a good overall description of height variations, it does not provide information relative to the shape of the surface and does not provide information about the frequency and regularity of their occurrence [1,7,14]. It also lacks details about wavelengths and is not responsive to minor changes in the profile. For example, different authors [10,14] describe the possibility of the same Ra value for a surface with profiles of different shapes and frequencies. A correlation between the cutting parameters and surface finish can be established when the valleys transform into peaks or the opposite. This argument cannot be established using Ra [9,16].

A single roughness parameter is insufficient to analyze surface texture or recognize patterns [17]. The amplitude parameters skewness (Rsk) and kurtosis (Rku) assess surface structure, surface defects, and wear conditions, offering a more comprehensive surface characterization [10,14,16]. Skewness (Rsk) [7,14] is an effective parameter to characterize the symmetry level within the distribution function. It is particularly responsive to occasional deep valleys or high peaks, allowing us to differentiate between asymmetrical profiles that might otherwise share the same Ra value [7]. Kurtosis (Rku) quantifies the sharpness of the probability density distribution within the profile by measuring the extent of pointedness or flatness in a distribution function [7,14]. The conjunct analysis of Rsk and Rku can precisely determine the surface condition and elucidate whether it exhibits excessively high peaks or valleys [17].

Considering the constraints highlighted in prior investigations, the present authors propose an analytical comparison between two different polishing methods, manual and mechanical, to establish a different approach for analyzing the surface roughness height parameters in dental acrylic resins.

2. Materials and Methods

2.1. Materials

2.1.1. Samples Preparation

Six samples of a CAD/CAM 3D printed resin (V-Print dentbase, VOCO GmbH, Cuxhaven, Germany), each measuring 20 × 20 × 3 mm, were tested. Table 1 describes the process, resources, and method, used to prepare the samples

Table 1. Sample preparation process.

Process	Resources	Method
Design	*CAD Asiga Composer 2.0* (Asiga Composer, ASIGA, Erfurt, Germany)	STL file
Impression	*Asiga Max UV 3D Printer* (ASIGA, Erfurt, Germany)	Digital Light Processing (DLP)
Cleaning	*Sonorex Super, RK 102H* (Bandelin, Berlin, Germany)	Isopropyl alcohol
Post-Processing	*Otoflash G17 G171, Flashing Unit* (NK-Optik GmbH, Baierbrunn, Germany)	$\lambda_{(wavelength)}$ = 580 nm

2.1.2. Polishing Protocol

Five specimens were subjected to two polishing protocols: manual and mechanized. A prototype of a mechanical polishing device (Figure 1), previously developed and published by the author [1], was used in this investigation. A sixth specimen was not submitted to any polishing protocol and served as a control.

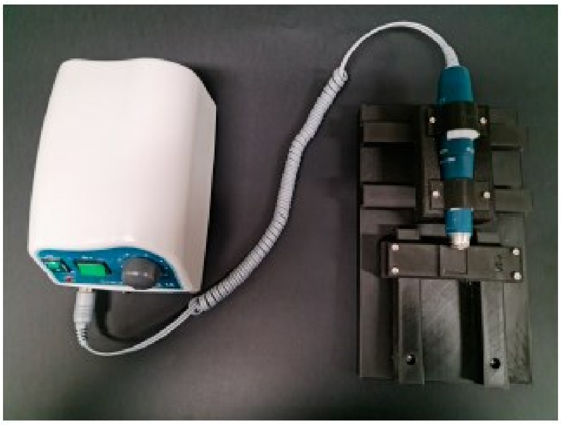


Figure 1. Mechanized polishing device [1].

All samples were polished following traditional steps described in ISO standard 20795-1:2008 [18] using a tungsten carbide bur with a thin crosscut followed by a JOTA® Kit 1877 DENTUR POLISH (Jota AG, Rüthi, Switzerland) sequence with a handpiece coupled to a micro-motor (STRONG 206, SAESHIN®, Daegu, Republic of Korea) at 5000 rpm. The manufacturer's instructions recommend using a bullet–shaped drill for acrylic prosthetic bases. In both methods, each drill (coarse grain, medium grain, and fine grain) was applied for 30 s. To reduce the wear effect of the drill upon contact with the samples, the polishing methods were applied sequentially.

The same five samples were used for both polishing techniques to ensure consistent processing conditions and reduce their impact on surface roughness. The manual technique was applied on one side, while the mechanized technique was applied on the opposite side, randomly determined.

The polishing protocol was standardized by a single operator. The mechanized technique involved a mechanized device. The intention behind this device was to standardize and control the polishing method by reducing the operator's associated variables. In the mechanized device, the handpiece is fixed on a support that glides over the sample surface. In the case of manual polishing, the operator holds the handpiece.

The repeatability of the polishing protocol between techniques was ensured by fixing the samples on the same support to ensure parallelism with the bur. The polishing direction was maintained.

Following the polishing process, the samples were immersed in distilled water and placed in an oven (EHRET BK 4106, EHRET GmbH, Mahlberg, Germany) at a constant temperature of 37 °C for 24 h to replicate the acrylic rehydration process for denture bases.

2.2. Methods

Surface roughness evaluation was performed using a contact profilometer (Hommelwerke with a linear unit LV-50 and T8000 controller, Hommelwerke, Germany).

The surface of the specimen was traversed by a diamond tip (length of 4.8 mm) with a constant load of 10 s and a constant speed of 0.5 m/s. Three measurements were taken from each test specimen on randomly selected measurement lines.

Surface roughness parameters and profilometric profiles were extracted. A primary profile was obtained (Profile P), unfiltered with a length l_t. Per definition, Profile P corresponds to the curve that appears when the actual surface of the material is cross-sectioned. A Gaussian filter was applied to the primary profile, resulting in a roughness profile (Profile R) with a length l_m used to calculate roughness parameters (Figure 2). Profile R refers to the curve in which only high-frequency components of the primary profile are recorded through a high-pass filter (cutoff value λ_c).

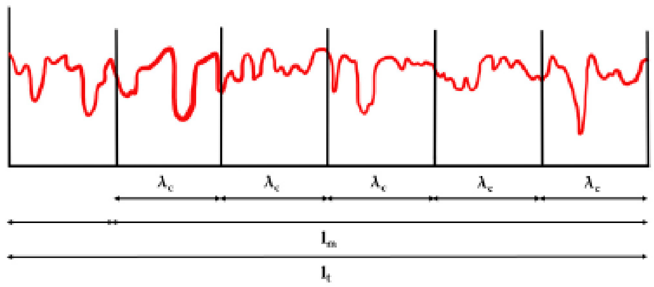


Figure 2. Primary profile (l_t); Roughness profile (l_m); Gaussian filter with a cut-off length (λ_c).

A Gaussian filter with a cut-off length (λ_c) was chosen according to the expected roughness threshold for microbial colonization (Ra = 0.2 μm) [2,19], as recommended by ISO 4288 [20]. Transverse (l_t) length was directly selected through the cut-off length selected (Table 2) (Figure 2) [15].

Table 2. Relationship between cut-off and transverse lengths (ISO 4288; 1997) [20].

Cut-Off (λ_c) mm	Transversing Length (l_t) mm
0.8	4.8

Selecting the correct filter parameter is important to the significance [20] of the measurement [15].

2.3. *Surface Roughness Parameters*

The authors propose the following approach to evaluate surface roughness in dental acrylic resins.

2.3.1. Arithmetical Mean Height

Arithmetical mean height describes the average of the absolute values along the sample length. Arithmetic mean roughness (Ra) refers to the filtered profile (l_m) and arithmetic mean height (Pa) refers to the primary unfiltered profile (l_t). Table 3 demonstrates the corresponding mathematical formulation described in ISO 4287 (1997)-surface texture [11].

Table 3. Comparison between arithmetic mean roughness and arithmetic mean profile [15].

Parameter	Description	Formula
Ra	Arithmetic mean roughness	$\frac{1}{l_m}\int_0^{l_m}\lvert y(x)\rvert dx$
Pa	Arithmetic mean profile	$\frac{1}{l_t}\int_0^{l_t}\lvert y(x)\rvert dx$

Figure 3 represents the differences between a filtered and an unfiltered roughness profile of a sample used in the present study. The filtered profile corresponds to a 4000 µm measuring length (l_m) while the unfiltered profile reaches a 4800 µm measuring length (l_t). The difference between both measuring lengths corresponds to the cut-off length selected (λ_c) (Table 2).

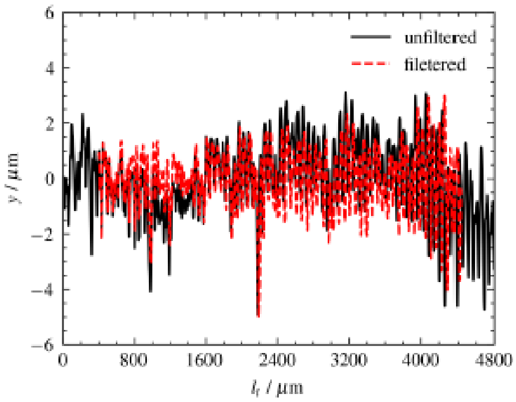
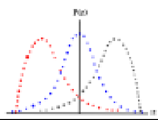


Figure 3. Roughness profile (y/l_t).

2.3.2. Skewness (Rsk)

Profile skewness describes the symmetry of the amplitude distribution curve at the profile mean line, as shown in Table 4.

Table 4. Amplitude of the distribution curve skewness [15].

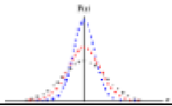
Value	Meaning	Graphic Representation [10]
Rsk < 0	Longer tail on the left of the distribution (red curve)	
	Symmetrical Gaussian distribution (blue curve)	
Rsk > 0	Longer tail on the right of the distribution (gray curve)	

A Gaussian distribution of the roughness profile is reflected by zero skewness. A surface characterized by negative skewness displays an increased number of local maxima above the mean, deviating from the symmetric pattern of a Gaussian distribution. For positive skewness, the converse occurs [9,10,17].

2.3.3. Kurtosis (Rku)

Kurtosis quantifies the sharpness of the probability density distribution within the profile being classified, as shown in Table 5.

Table 5. Amplitude of the distribution curve—Kurtosis [15].

Value	Meaning	Graphic Representation [10]
Rku < 3	Flat amplitude distribution (gray curve)	
Rku = 3	Symmetrical Gaussian distribution (red curve)	
Rku > 3	Sharp amplitude distribution (blue curve)	

A Gaussian distribution of the roughness profile is reflected in a kurtosis value of 3. A surface with lower probably of occurrence of extreme values compared to Gaussian distribution is reflected in a kurtosis < 3.The opposite occurs for a kurtosis > 3 [9,10,17].

2.4. *Statistical Analysis*

The surface roughness values obtained from the profilometric reading were subjected to a descriptive and inferential statistical analysis of the data using IBM® SPSS® version 25.0 (IBM, Berlin, Germany) with $p < 0.05$. Arithmetic mean roughness values (Ra and Pa) were represented using the mean and standard deviation and 95% confidence interval of the mean. Skewness (Rsk and Psk) and kurtosis (Rku e Pku) were also represented. High kurtosis values indicate a sharp amplitude distribution with large peaks and valleys. Negative skewness suggests a concentration of material near the top of the profile and a plateau-like surface. In addition, the variation coefficient (CV), defined as the ratio between standard deviation and average value, was utilized. The two-way analysis of variance (ANOVA) with Bonferroni and the Games–Howell post-hoc test were used to compare the distribution of surface roughness Pa and Ra between polishing techniques.

3. Results

Table 6 shows the mean and standard deviation roughness parameters measured for the unfiltered (Pa) and filtered (Ra) groups.

Table 6. Dispersion measures of roughness for different polishing techniques.

Measure	Sample			ANOVA	
	Mechanized	Manual	Control	F	*p*-Value
Pa (µm), mean ± SD	1.49 ± 0.50	1.49 ± 0.50	11.11 ± 4.18	90.139	<0.001
Ra (µm), mean ± SD	0.89 ± 0.32 *	0.52 ± 0.17 *	2.13 ± 0.14 *	53.028	<0.001

* significant differences between groups on post-hoc analysis; F, ANOVA F-statistic.

In terms of Pa, the mechanized technique demonstrated the lowest mean value at 1.49 µm, followed closely by the manual technique at 1.49 µm. The control technique exhibited the highest mean value at 11.11 µm (Table 6). The ANOVA F-statistic of 90.139, along with the associated *p*-value of <0.001, underscores a statistically significant difference in Pa distribution among the three techniques. However, the lack of homogeneity among variances between the samples precluded the identification of significant differences in the post-hoc analysis, as revealed by the Games–Howell test.

Similarly, for Ra, the mechanized technique displayed the lowest mean value at 0.89 µm, followed by the manual technique at 0.52 µm, and the control technique at 2.13 µm. The ANOVA F-statistic of 53.028, coupled with a *p*-value of <0.001, indicates a statistically significant difference in the Ra distribution among the three techniques. Post hoc analysis further corroborated noteworthy differences in Ra between all three techniques, with both the mechanized and manual techniques surpassing the control technique in performance.

The coefficient of variation (CV) for Pa displayed relatively similar values across the three techniques, ranging from 0.334 for mechanized to 0.377 for control (Table 7).

Table 7. Coefficient of variation (CV) for different polishing techniques.

Coefficient of Variation (CV)	Sample		
	Mechanized	Manual	Control
Pa (µm)	0.334	0.337	0.377
Ra (µm)	0.362	0.323	0.067

By contrast, the CV for Ra exhibited a distinct pattern, with the control group registering a lower value of 0.067 compared to 0.362 for mechanized and 0.323 for manual.

Tables 8 and 9 show the filtered and unfiltered groups for skewness (Rsk/Psk) and kurtosis (Rku/Psk), respectively.

Table 8. Skewness data for two groups of specimens.

Statistics	Psk	Rsk
Control	−0.452	−0.282
Mechanized	−0.893	−1.153
Manual	−0.416	−1.365

Table 9. Kurtosis data for two groups of specimens.

Statistics	Pku	Rku
Control	0.461	−0.032
Mechanized	3.348	4.921
Manual	0.819	8.267

The skewness values indicate a leftward tendency for the three categories, aligning with the text's observation of heightened skewness heterogeneity in this category. The mechanized and manual categories exhibit a larger magnitude value compared to the control. A more pronounced distribution with lower values is found in the manual category (Table 7).

The kurtosis values indicate a platykurtic distribution (Pku/Rku < 3) for the control category. After the polishing procedures (mechanized and manual), the probability of occurrence of extreme values increased with a distribution tendency for leptokurtic (Pku/Pku > 3). On the other hand, a platykurtic distribution (Pku = 0.819) is found on the profile of kurtosis for manually polished samples (Table 9).

Figure 4 represents the height distribution curve for the filtered and unfiltered profiles: control (A, B), mechanically polished (1A, 1B), and manually polished (2A, 2B).

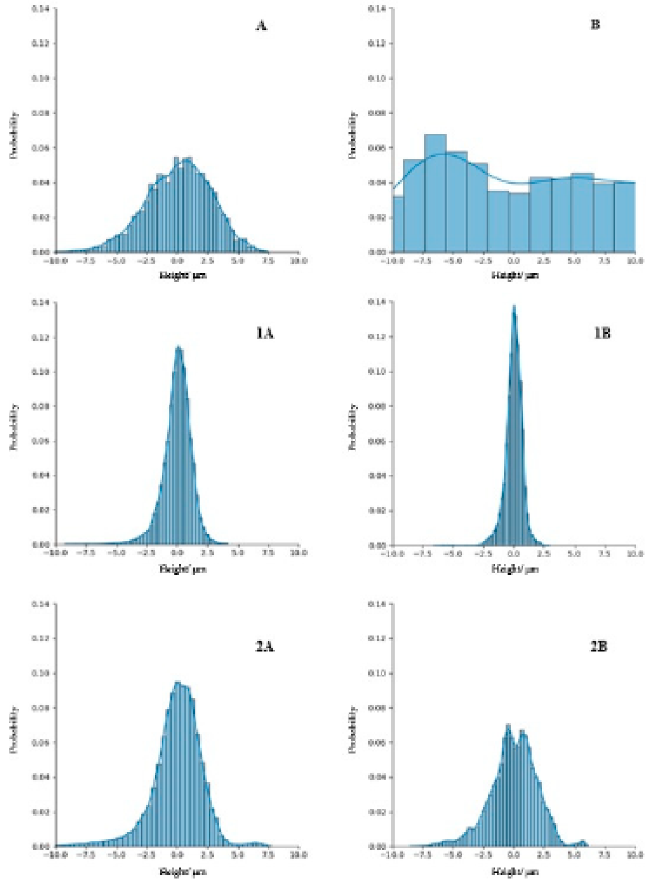


Figure 4. Height distribution curve—filtered profile ((**A**) Control sample; (**1A**) Mechanized polished samples; (**2A**) Manually polished samples); unfiltered profile ((**B**) Control sample; (**1B**) Mechanized polished samples; (**2B**) Manual polished samples).

4. Discussion

PMMA remains the predominant choice for denture base materials. Additives such as polymerization initiators, accelerators, bonding agents, and colorants have been incorporated into the base composition. These additives play a crucial role in shaping the physical and chemical properties of these materials. Among these properties, surface roughness influences the retention of microbial plaque in tissues in contact with the denture base [1,6,19].

The inherent physical characteristics of surface roughness are influenced by factors such as the operator's manual dexterity, the polishing protocol employed, and the inherent composition of the material itself.

In the literature [4,21], there is a lack of knowledge concerning the development of an effective mechanical protocol for polishing acrylic resin surfaces. To overcome this deficiency, a prototype was developed [1]. The authors proved its validity by determining significant differences between resin groups polished with the prototype ($p = 0.031$) [1]. Nevertheless, only differences in average roughness values (Ra) between the groups were assessed. One limitation was the absence of other height parameters to compare both polishing techniques (mechanized and manual).

Selecting the most suitable and pertinent surface roughness parameters to monitor desired surface properties is challenging. The need to promptly identify a subset of parameters that correlate with surface functionality has been emphasized [17].

As studied for other materials, the present authors propose the introduction of a primary profile to the analyses of a surface. The primary profile is the most critical aspect of evaluating surface roughness because it directly represents surface details, including peaks and valleys and all height variations [10,14,15]. The main parameter used to characterize the surface roughness of acrylic resins is Ra. It is an optimal value for evaluating the effect of surface polishing and finishing protocols because it considers variations in height and depth roughness [4,9,15,19,21]. However, it only addresses the profile's vertical deviation, failing to offer insights into the slopes, shapes, asperity sizes, or the frequency and regularity of their occurrence [15,16]. These features directly define the functionality of a surface in relation to bacterial adhesion, microbial growth, and stress [17,22].

Pa, directly extracted from the primary profile, can be considered an extension of Ra to the profile, as shown in Table 3. Both represent the deviation of each point's height from the arithmetical mean in different profiles [23]. From a clinical perspective, the significance of Pa is relevant because it addresses the actual profile of the resin surface. Pa represents the average of unfiltered peak and valley distances from the mean surface profile. The observed differences are comparable to the Ra results of the filtering operation, eliminating the deepest asperities of the surface [21]. Significant differences were found in three groups ($p < 0.01$) for Ra; however, the heterogeneity among samples for Pa makes it difficult to determine these significant differences. Specific parameters, such as skewness and kurtosis, are described to differentiate surfaces with different shapes and the same value for Pa [14], as described in the values for the mechanical and manual techniques (1.49 ± 0.50 µm) (Table 5). Figure 4(1B,2B), show differences between the distribution curves, respectively.

Height distribution is indicated by height probability density, which compares the probability of having a given surface height relative to the centerline for each group, and is shown in Figure 4. Beyond the average roughness values, skewness (Rsk/Psk) and kurtosis (Rku/Pku) should be considered to provide information about the distribution of irregular heights on the surface [14,17]. Previous studies [4,21] showed a quasi-normal Gaussian distribution for mechanically polished specimens and a clearly asymmetric distribution for manually polished specimens. By contrast, after the polishing procedure (manual or mechanized), the present authors verified that the height distribution displayed an increase in kurtosis and a leftward skewness tendency, signifying asymmetry in height data and extreme values associated with valleys (Tables 8 and 9). Negative skewness describes a significant number of local maxima below the mean, as compared to a Gaussian distribution [10,14,24], which corresponds to areas with deep valleys and a lack of high peaks. A parameter Sku >3 (leptokurtic) describes surfaces with high peaks and deep valleys. By combining both parameters, a plateau-like smooth surface with deep valleys is observed, similar to the mechanized samples (Figure 4, 1A and 2A).

In terms of CV, the control group registered the lowest CV value of 0.067 compared to the polishing techniques, exhibiting a height distribution with lower kurtosis (Table 9) and a skewness near zero (Table 8).

This finding implies that the control group, directly resulting from the processing technique, produces a more uniform surface finish for Ra than the other two techniques, which increases the dispersion of surface roughness values. The literature also describes that surface height distribution features are contingent on the processing method used [6]. The ultimate shape of surfaces generated through cumulative processes, such as 3D printed resin, results from the aggregation of numerous random local events, displaying a cumulative effect that follows a Gaussian form (Rsk = 0 and Rku = 3) (Figure 4) [10,14]. Similar values were obtained for Pa, and a distinctive pattern was seen for Ra. Surface roughness parameters revealed an increased CV value for mechanically polished specimens (Table 7). Measurements of Pa and Ra for manual polished resins reflect not only the intrinsic roughness characteristics of the surface, but also the influence of the operator's factors, such as the technician's skill, wrist stability, attention level, and other relevant considerations associated with the manual polishing process. In contrast to the results obtained by Corsalini [21], mechanized polishing exhibited significantly higher Ra dispersion values. The efficiency of mechanized over manual protocols is questionable since it did not have the most reliable process for value dispersion or the Ra and Pa values obtained in relation to the control group.

Notably, surface polishing influences the features of height data distribution [7,24]. Improvements to the polishing device and the present protocol should be implemented. As previously mentioned [4,21], a protocol not dependent on the operator is more reliable. Obstacles to clinical usage of the proposed mechanical polishing system include the curvature exhibited on a denture base surface and the shape irregularity of removable prostheses [21].

This is a preliminary and analytical study. Studies analyzing this specific approach are not described in the literature for prosthetic acrylic resins. However, the integration of skewness and kurtosis has already been studied in other dental materials. For example, the authors performed a functional analysis on the shear bond strength of prosthetic rehabilitations in zirconia ceramics and resorted to these parameters [22].

Table 10 summarizes the differences between both approaches and clarifies the importance of analyzing additional parameters.

Table 10. Comparison between the conventional and proposed approach.

Ra:	Pa:
• Result of a filtering operation that excludes information from a surface;	• Direct extraction of the primary profile.
• Only addresses surface irregularities in a vertical direction; • Height average deviation to the mean line (does not differentiate peaks and valleys); • Same Ra value with different tribological performances.	**Skewness and Kurtosis** • Height distribution and tip geometry of peaks and valleys; • Describes how the roughness is distributed along the profile; • Differentiates between different tribological performances.

Future studies should emphasize the clinical context of the presented parameters when assessing surface characteristics and applications.

PMMA exhibits relatively low hardness, and its surface is prone to daily wear. Roughness parameters undergo continuous changes over time.

The functional performance of a surface is closely linked to the surface finish, including the surface layer's texture and mechanical properties. These properties accompany daily use and consequent wear in the oral cavity [8]. As studied in other materials [8,9,17], skewness and kurtosis in surface roughness are critical parameters for clinically assessing retention and fit, fatigue life, corrosion, resistance, wear resistance, tissue response, aesthetics, cleaning, and maintenance of dental prostheses made of acrylic resins. For example, Das et al. [17] emphasize the importance of selecting abrasive grain sizes, as they can directly modify surface roughness and functionality, such as susceptibility to microbial contamination or the accumulation of fluid/debris. Grzesik (2016) [8] exhibited a strong correlation between skewness and kurtosis with the grit size of abrasive tools. With the additional influence of the primary profile, professionals can make informed decisions to optimize the surface finishing process of acrylic resins.

5. Conclusions

One significant challenge in surface-related research is selecting meaningful roughness parameters that exhibit a fundamental correlation with surface formation mechanisms and behavior, which are crucial for bacteria adhesion.

The conventional approach using Ra does not address the actual profile of the resin surface and only assesses vertical deviations. The proposed approach enriches the understanding of how these parameters influence the overall performance and functionality of acrylic dental resins within clinical scenarios. The primary profile (Pa) serves as the foundation for assessing and characterizing surface roughness. Parameters such as skewness and kurtosis were presented to provide information relative to the shape of the surface and differentiate between tribological surface behaviors.

Author Contributions: Conceptualization, M.M.Q., A.C., C.F., P.F. and J.M.; Methodology, M.M.Q., H.S. and C.F.; Software, C.F.; Validation, M.M.Q. and C.F.; Formal analysis, A.C., P.F. and J.M.; Investigation, M.M.Q. and C.F.; Resources, M.M.Q., C.F. and A.C.; Data curation, M.M.Q.; Writing—original draft preparation, M.M.Q. and C.F.; Writing—review and editing, M.M.Q., C.F., A.C., P.F. and J.M.; Visualization, A.C., P.F., and J.M.; Supervision, A.C., P.F. and J.M.; Project administration, A.C., P.F. and J.M.; Funding acquisition, A.C. and P.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by National Funds through FCT—Fundação para a Ciência e a Tecnologia, I.P., under the project UIDB/04279/2020. Carlos Fernandes is grateful for funding through LAETA, Portugal, in the framework of project UID/50022/2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Acknowledgments: VOCO dental, Jota AG.

Conflicts of Interest: The authors declare no conflict of interest.

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10.1.2. PAPER 2

Quezada, M.M., Fernandes, C.M.d.C.G., Martín, J.M. *et al.* Influence of different processing techniques for prosthetic acrylic resins in the surface roughness parameters: a research article. *BMC Oral Health* 24, 641 (2024).

ISSN: 1472-6831

Impact factor: 3.747 JCR Science Edition: 2022.

Category: Dentistry (miscellaneous)

Position in the category: Q1

Quezada *et al. BMC Oral Health* (2024) 24:641
https://doi.org/10.1186/s12903-024-04397-1

BMC Oral Health

RESEARCH Open Access

Influence of different processing techniques for prosthetic acrylic resins in the surface roughness parameters: a research article

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Abstract

Background Different processing techniques are employed to obtain poly (methyl methacrylate) (PMMA) with consistent surface quality in terms of topography and tribological function. The purpose of this research is to evaluate its influence on the surface height distribution.

Methods In this research, samples of conventional and CAD/CAM acrylic resins were prepared. The following surface roughness parameters were extracted from the profilometric readings: arithmetic mean roughness (Pa), skewness (Psk) and kurtosis (Pku). Profilometric profiles were additionally obtained.

Results The average roughness (Pa) with the conventional technique was significantly higher compared to CAD/CAM ($t=4.595$; $P<0.001$). Heat-cured resins presented the highest mean Pa ($F=6.975$; $P=0.06$). Heat-cured and milled resins show lower coefficient variation (CV) values, indicating more consistent surface finishing. The surface profiles revealed distinct characteristics in terms of skewness and kurtosis.

Conclusions The surface processing method, chemical composition and resin type significantly influence the surface finishing of the resin. The CAD/CAM resins exhibited superior results in terms of surface arithmetic mean roughness (Pa). However, heat-cured resin revealed to present the better surface consistency.

Keywords Polymers, Polymethyl methacrylate, Surface properties

Background

In accordance with Specification No. 12 of the American Dental Association (ADA) [1], polymers for prosthetic bases are classified into several types, depending on the polymerization reaction and their composition [2–5]. However, poly (methyl methacrylate) (PMMA) remains the most frequently used [4, 6, 7] due to its favourable characteristics, including processing and pigmentation, reduced toxicity and satisfactory mechanical properties [2].

Conventional PMMA is mainly accessible in the form of a powder-liquid system. The powder incorporates the polymer PMMA with the addition of additives, as

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pigments or acrylic synthetic fibers to mimic the aesthetics of oral tissues and to calibrate the physical properties [4, 6]. The liquid part contains a monomer of methyl methacrylate (MMA) in addition to cross-linking agents and inhibitors [4]. PMMA is derived from a polymerization reaction wherein the conversion of MMA into PMMA occurs during a curing process, activated either by chemical products, light or heat [5, 7].

Computer-aided design and computer-aided manufacturing (CAD/CAM) have been introduced as a method for producing PMMA for prosthetic bases [4]. A notable advantage appears to be the controlled temperature and pressure polymerization of prefabricated blanks of PMMA. Consequently, these materials are commonly referred to as high–performance polymers (HPPs) [3–5, 8].

Numerous researchers conducted comparisons of the properties between conventionally and CAD/CAM manufactured PMMA [3–6, 8]. The chemistry of CAD/CAM PMMA is similar to that of conventional heat cured PMMA [4, 9]. However, CAD/CAM PMMA exhibits advantages, including surface properties, flexural strength, and flexural modulus [3, 4, 6]. .

Different processing techniques are employed to obtain PMMA with the specified dimensional tolerances and surface quality consistency, to achieve the desired shapes [10, 11]. This must be examined from two perspectives: process control and tribological functionality [10, 12]. The functional properties are related to the 2D and 3D surface roughness, waviness and surface texture [13]. The surface topography is a random structure composed of microscopic peaks and valleys formed during the manufacturing process. As a result, macro roughness and micro roughness can occur [6, 11, 13].

The challenge arises to the necessity of selecting appropriate surface parameters to monitor whether the desired functional surface properties are achieved. The most common metric used to analyze surface roughness is Ra (arithmetical mean roughness). This parameter summarizes height variations; however, it lacks into surface shape and does not offer details regarding the frequency or regularity of occurrence [14].

Most surfaces exhibit a degree of randomness that may follow a Gaussian (normal) or non-Gaussian distribution. The specific characteristics of a surface's height distribution are influenced by the method used to develop the surface. The Gaussian distribution has become a fundamental tool for classifying surface properties [15]. Surface parameters, such as skewness and kurtosis of the height distribution, are frequently used to characterize Gaussian topographies [16, 17]. Various authors have described the potential occurrence of identical Ra value for surfaces with different shapes and frequencies [15, 17].

Table 1 Description of the resins used for this research

Name	Commercial brand	Country of origin
Probase® cold	Ivoclar Vivadent	Liechtenstein
Probase® hot	Ivoclar Vivadent	Liechtenstein
iflex™	tcs®	USA
CediTEC DB	VOCO® GmbH	Germany
V-Print dentbase	VOCO® GmbH	Germany

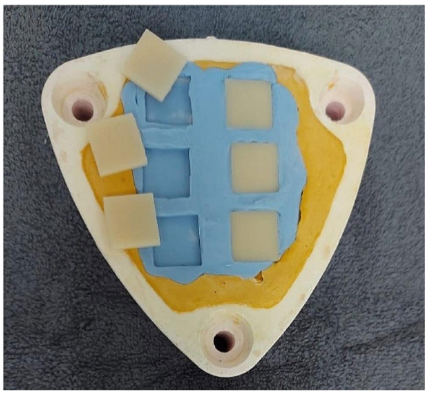

Fig. 1 Silicone molds with predefined dimensions (20 × 20 × 3 mm)

This preliminary research intends to evaluate the influence of different processing techniques for prosthetic acrylic resins on the surface roughness parameters.

Methods

Five denture base acrylic resins were selected as shown in Table 1. Five quadrangular-shaped specimens (20×20×3 mm) were manufactured according to the instructions and specific standards [18].

For the specimens using conventional resin (self-cured, heat-cured and injected molded) (Table 2), silicone molds were prepared with the predefined dimensions (Fig. 1).

According to the manufacturer's instructions, presented in Table 2, the self-cured denture base acrylic resin Probase® Cold and the heat-cured denture base acrylic resin Probase® Hot were obtained by a conventional flasking technique (Fig. 1). Both polymerization reactions were carried out in a pressure device for 30 min at 23 °C and for 45 min at 100 °C, respectively.

The resin tube iFlex™ was placed on tcs® Digital Furnace (tcs® Dental Inc., California) and injected with tcs® Handheld JP90 (tcs® Dental Inc., California) (Fig. 2). The polymerization occurred inside the muffle at 23±2 °C.

For the milled samples, the virtual design of the specimen was obtained with CAD software SolidWorks®, which was converted to a standard tessellation language (STL) file. Then, it was sent to a DWX-52D milling

Table 2 Characteristics of the resins

Material	Composition		Ratio	Curing method
Probase® Cold	**P**: PMMA Dibenzoyl peroxide	**Li**: MMA	P/Li 20.5/10 (g/ml)	Self – curing: 23 ºC for 30 min (Conventional)
Probase® Hot	**P**: PMMA Dibenzoyl peroxide	**Li**: MMA 1–4 butanediol dimethacrylate	P/Li 22,5/10 (g/ml)	Heat – curing: 100 ºC for 45 min (Conventional)
iFlex™	Polyolefin			Injected molded (Conventional)
Ceditec DB	PMMA		99%	Milling (CAD/CAM)
V-Print dentbase	**Li**: UDMA Bis – EMA TEGDMA		50–100% 25–50% 5–10%	Digital light processing method (DLP) (CAD/CAM)

P – Powder; Li – Liquid; PMMA– Poly Methyl Methacrylate; UDMA– Urethane Dimethacrylate; Bis – EMA – Bisphenol-A-Ethoxylate Dimethacrylate; HEMA – Hydroxyethyl

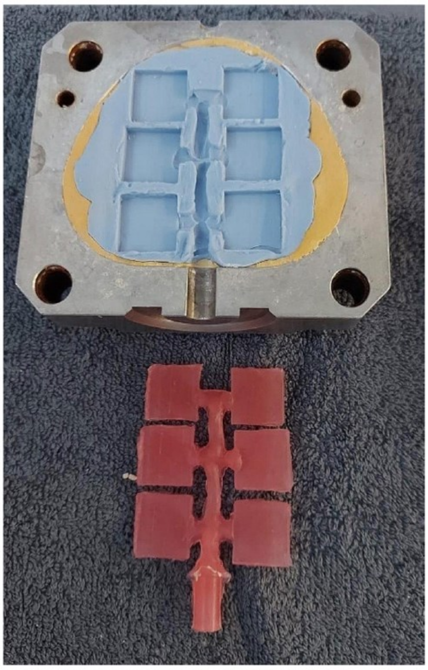

Fig. 2 Injection technique on the predefined silicone molds

machine (DWX Series, Spain). A PPMA pre-polymerized block (*CediTEC DB*, VOCO®, GmbH, Germany) with 98, 5×30 mm dimensions was placed on the appropriate support for the size. A milling bur used at a 90º angle relative to the block position. The milling process was applied dry.

The 3D printed samples were virtually designed with CAD Asiga Composer (Asiga Composer, ASIGA, Germany), which was converted to an STL file. It was sent to an Asiga Max UV 3D printer (ASIGA, Germany). The specimens were obtained through the digital light processing method (DLP). After printing, the specimens were submitted to an ultrasonic bath with isopropyl alcohol for 2 min, and the post–processing procedure was executed with an Otoflash G171 flashing unit (NK-Optik GmbH, Germany): 10 flashes/second with a wavelength of 385 nm.

No surface treatment was applied to any of the samples after processing, and sterilized compartments were used to avoid any interference or contamination. Then, the specimens were subjected to a profilometer (Hommelwerke LV-50 with linear unit and T800 controller, Hommelwerke, Germany) reading. The surface of the specimens was measured by a stylus probe with a diamond tip (length of 4.8 mm) at a constant speed of 0.5 m/s. The surface roughness parameters were directly obtained from the primary profile (Profile P). The use of Profile P is clinically relevant since it represents the curve formed when the actual surface of the material is cross-sectioned, without the use of a Gaussian filter [14].

The data were analysed using IBM® SPSS® Statistics for Macintosh, version 27 (IBM Corporation, USA). Pa roughness values are represented using the mean and standard deviation. A descriptive analysis was used to analyze skewness (Psk), and kurtosis (Pku). High kurtosis values indicate a sharp amplitude distribution with large peaks and valleys. A negative skewness suggests a concentration of the material near the top of the profile and a plateau-like surface. In addition, the percent variation coefficient (CV), defined as the ratio between the standard deviation and the average value was utilized.

Table 3 Roughness data for different processing methods and resin types

Overall Pa (μm), mean ± SD					Inter-group comparison statistics
Conventional		**CAD/CAM**			
11.35 ± 4.68		2.26 ± 1.29			t = 4.595; $P < 0.001$
Resin-specific Pa (μm), mean ± SD					**Inter-group comparison statistics**
Self-cured	**Injected molded**	**Heat-cured**	**3D printed**	**Milled**	
11.77 ± 5.26	8.19 ± 3.20	14.10 ± 4.80[a,b]	3.00 ± 1.48[b]	1.51 ± 0.56[a]	F = 6.975; $P = 0.06$

a, b: significant differences in pairs of resins using Bonferroni post-hoc correction at $P < 0.05$

Table 4 Measures of roughness dispersion for polishing techniques and resin types

Resin types and polishing techniques	Variation coefficient (CV)	Skewness (Psk)	Kurtosis (Pku)
Conventional			
Self-cured	0.447	-0.453	0.462
Injected molded	0.391	0.872	1.068
Heat-cured	0.341	0.339	0.267
CAD/CAM			
3D printed	0.493	0.201	1.578
Milled	0.371	-0.135	0.138

Two-way Analysis of Variance (ANOVA) with the Bonferroni post-hoc correction for a small sample size and predicted data not normally distributed was used to compare the distribution of surface arithmetic mean roughness (Pa) between different resin types. In order to test the means between two groups, Student's t test was employed to assess differences in the distribution of Pa between pairs of resins.

Results

Table 3 compares roughness data for different processing techniques and resin types. The overall mean roughness (Pa) for conventional techniques is 11.35±4.68 µm, significantly higher than CAD/CAM techniques at 2.26±1.29 µm (t=4.595; $P<0.001$), indicating that CAD/CAM yields lower overall Pa among resin types, heat-cured resins stand out with the highest mean Pa at 14.10±4.80 µm, showing significant differences in intergroup comparison statistics (F=6.975; $P=0.06$). Post-hoc tests highlight significant differences, with heat-cured resins differing from 3D printed ($P=0.034$) and milled resins ($P=0.015$).

Table 4 provides an analysis to the surface roughness measurements for dental acrylic resins and the corresponding processing techniques. The variation coefficient (CV) indicates variability in roughness. 3D printed and self-cured resins have higher CV values (3D printed: CV=0.493, self-cured: CV=0.447), suggesting greater variability. In contrast, heat-cured (0.341) and milled resins show lower CV values (0.371). Surface profiles also reveal distinct characteristics. Self-cured (-0.453) and milled (-0.135) resins have a plateau-like surface with negative skewness, while injected molded resins show sharp variations with positive skewness (0.872) and substantial kurtosis (1.068).

Surface profiles also reveal distinct characteristics (Fig. 3).

Self-cured (-0.453) and milled (-0.135) resins have a plateau-like surface with negative skewness, while injected molded resins show sharp variations with positive skewness (0.872) and substantial kurtosis (1.068) (Table 4).

Discussion

In terms of analysis of the surface properties, the authors proposed a different approach to the assessment using the following parameters: skewness (Psk), kurtosis (Pku) and arithmetic mean roughness (Pa) [14]. The validation of the use of Pa instead of Ra, commonly used, had already been demonstrated [14, 19, 20]. The results published by the authors of the present research were reused for the present analysis [14].

Considering the existing drawbacks between the mechanical and physical properties of conventional PMMA, new processing methodologies were developed [4, 8, 9, 21]. Superior surface properties in comparison to conventional PMMA may be attributed to the unique processing method of the CAD/CAM PMMA in which high temperatures, pressure and lower levels of residual monomer are used to obtain pre-polymerized PMMA, in case of subtractive technique, or a layer by layer polymerization, in case of additive technique [5, 6, 21]. In general, when compared the two processes in relation to surface roughness, a significant difference in mean Pa (t=4.595; $p<0.001$) highlights the processing method impact on surface finishing. In the analysis in pairs, heat-cured differs significantly from 3D printed ($p=0.0034$) and milled resins ($p=0.015$).

Considering the chemical composition, several studies reveals that the composition of the CAD/CAM PMMA

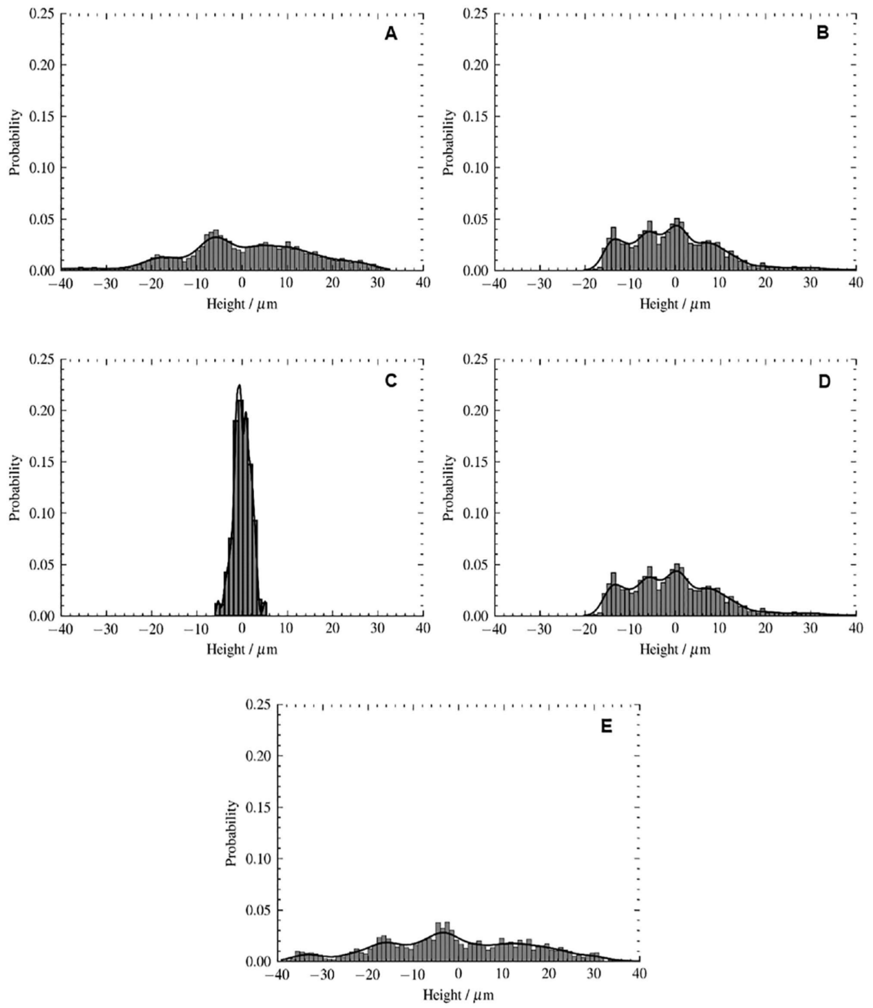

Fig. 3 Probability of having a given height of the surface for the specimens according to resin processing type: **A** (self-cured), **B** (heat-cured), **C** (3D printed), **D** (milled), **E** (injected molded)

is similar to that of conventional PMMA [4, 9]. In contrast with what is presented in Table 2, also the chemical composition of PMMA polymers reveals influence on the surface roughness. Heat cured resins reveals the highest values of Pa in contrast with the results obtained by Berger et al. [22]. . The reaction of polymerization is activated by heat, therefore it is expected that the degree of conversion of MMA monomer occurs almost totally. Additionally, the polymer that constitute has a lower granule size in comparison with self cured resins, for example. A direct effect on the surface roughness by the reaction initiatior can be established as this resins uses benzoyl peroxide and 1–4 butanediol dimethacrylate [6, 22].

When assessing the overall roughness level, surface height distribution symmetry is a crucial aspect related to surface characteristics. As a result, it has the potential to measure the consistency of surface texture [16, 23–25]. Probability density and distribution curves are determined upon the nature of the processing method [15]. The variation coefficient is a measure of dispersion in relation to mean values in this study related to the surface roughness (Pa). The results of CV reveal lower variation on the overall Pa in milled (CV=0.371), heat-cured resins (CV=0.341) which means a higher probability density and a lower dispersion of Pa values in the distribution curve. The opposite appears in the self cured resins (CV=0.447) and 3D printed (CV=0.899). In terms of texture considerations, a lower CV indicates a more homogeneous surface. Heat-cured resin presented the higher Pa values with the lowest CV, indicating a more consistent surface quality, in comparison with milled resin with the lowest values of Pa. The opposite also occurs for hight CV value with a more heterogenous surface.

The correlation skewness (Psk) and kurtosis (Pku) provides valuable insight for analyzing the symmetry of a texture amplitude and to understand whether it contains inordinate high peaks/valleys on the surface and its influence on the bacterial adhesion [10, 15, 26, 27]. A non–Gaussian distribution of the roughness profile is characterized by Psk and is responsive to sporadic deep valleys or high peaks, as it quantifies the symmetry of the profile distribution with respect to its central line [10, 15]. Negative skewness pertains to profiles that are more prevalent in deep valleys, as occurs in self-cured (Psk = -0.453) and milled (Psk = -0.135). Further, non-Gaussian surfaces with relatively flat peaks and valleys are indicated by a Pku value less than 3, presented in all types of resins. Injected molded resins contrast with sharp variations with positive skewness (0.872) and substantial kurtosis (1.068). The higher Pku value indicates that the surface contains extreme peaks or valleys [23].

Despite the fact that the present research presents an “in vitro” design, further studies should proceed with the evaluation of the clinical implication related to the parameters Pa, Psk and Pku. First, in terms of selecting the appropriate polishing protocol for each type of acrylic resin, considering different processing techniques, their chemical composition, and consequently, the implications in terms of surface properties, such as the behaviour of roughness along the profile of a surface. Second, there is a lack of consensus regarding the minimum level for microbial adhesion and could differ according to the acrylic used and the hability of the microorganism to adhere to different surfaces [26, 27]. Studies report that microorganisms appear to have a preference for adhesion on surfaces with scratches and grooves and not necessarily with higher Pa values [26]. Therefore, the surface topography may have a greater influence on the bacterial adhesion than the roughness parameter value itself. A consensus should be establish on microbial adhesion thresholds and explore the interaction between surface topography and bacterial adherence.Two main limitation can be displayed. First, only five commercial brands of acrylic resins for prosthetic bases were tested in terms of composition and processing technique. Second, in relation to the shape of the test specimens, the quadrangular-shaped specimens do not resemble the complexity shape of the prosthetic bases at the clinical level.

Conclusions

This research undertook a comprehensive analysis of surface properties in acrylic resins using the parameters Pa, skewness and kurtosis. The surface processing method has a direct influence on the surface behavior. The distribution height curve characterizes the surface topography of manufacturing procedures. CAD/CAM resins exhibited superior results in terms of surface roughness, although, heat-cured resin revealed to present a better surface consistency. A focus on achieving optimal surface properties should extend to the selection of appropriate polishing protocols based on resin's type, processing technique and chemical compostion.

Acknowledgements
VOCO dental, Jota AG.

Author contributions
Conceptualization, M.M.Q., A.C., C.F., P.F. and J.M.; Methodology, M.M.Q. and C.F.; Software, C.F.; Validation, M.M.Q. and C.F.; Formal analysis, A.C., P.F. and J.M.; Investigation, M.M.Q. and C.F.; Resources, M.M.Q., C.F. and A.C.; Data curation, M.M.Q.; Writing-original draft preparation, M.M.Q. and C.F.; Writing—review and editing, M.M.Q., C.F., A.C., P.F. and J.M.; Visualization, A.C., P.F., and J.M.; Supervision, A.C., P.F. and J.M.; Project administration, A.C., P.F. and J.M.; Funding acquisition, A.C. and P.F. All authors have read and agreed to the published version of the manuscript.

Funding
This work was financially supported by National Funds through FCT—Fundação para a Ciência e a Tecnologia, I.P., under the project UIDB/04279/2020. Carlos Fernandes is grateful for funding through LAETA, Portugal, in the framework of project UID/50022/2020.

Data availability
All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no conflict of interest.

Received: 18 March 2024 / Accepted: 22 May 2024
Published online: 30 May 2024

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