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In Vitro Effect of Air-abrasion Operating Parameters on Dynamic Cutting Characteristics of Alumina and Bio-active Glass Powders

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Clinical Relevance

Bio-active glass (BAG) powder exhibits more air-abrasion conservative cutting characteristics compared to alumina powder, particularly within specific operating parameters. Clinical air-abrasion use should be preceded by studying the powder flow rate to identify the factors affecting the abrasive powder propulsion.

SUMMARY

Minimally invasive dentistry advocates the maintenance of all repairable tooth structures during operative caries management in combination with remineralization strategies. This study evaluated the effect of air-abrasion operating parameters on its cutting efficiency/pattern using bio-active glass (BAG) powder and alumina powder as a control in order to develop its use as a minimally invasive operative technique. The cutting efficiency/pattern assessment on an enamel analogue, Macor, was preceded by studying the powder flow rate (PFR) of two different commercial intraoral air-abrasion units with differing powder-air admix systems. The parameters tested included air pressure, powder flow rate, nozzle-substrate distance, nozzle angle, shrouding the air stream with a curtain of water, and the chemistry of abrasive powder. The abraded troughs were scanned and analyzed using confocal white light profilometry and MountainsMap surface analysis software. Data were analyzed statistically using one-way and repeated-measures analysis of variance tests (*p*=0.05). The air-abrasion unit using a vibration mechanism to admix the abrasive powder

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with the air stream exhibited a constant PFR regardless of the set air pressure. Significant differences in cutting efficiency were observed according to the tested parameters ($p<0.05$). Alumina powder removed significantly more material than did BAG powder. Using low air pressure and suitable consideration of the effect of air-abrasion parameters on cutting efficiency/patterns can improve the ultraconservative cutting characteristics of BAG air-abrasion, thereby allowing an introduction of this technology for the controlled cleaning/removal of enamel, where it is indicated clinically.

INTRODUCTION

Minimally invasive dentistry (MID) encourages the preparation of the smallest cavity possible, maintaining the presence of as much repairable tissue as possible, and relying on adhesion techniques to achieve the retention and seal of the overlying restorative materials.[1-4] Air-abrasion cuts tooth tissue through the use of kinetics to blast away surface hard tissues.[5] The variables controlling air-abrasion cutting efficiency (and, therefore, its potential intrinsic ability to remove tissues selectively) can be divided into three main categories: 1) the built-in physics and mechanics of the equipment, which includes the powder-air admix mechanism, powder flow rate (PFR), powder volume reservoir, nozzle output pressure, and water shrouding the powder stream; 2) the parameters controlled by the operator, including the nozzle angle, nozzle-substrate distance, nozzle movement speed, and the targeted substrate itself; and 3) the variations found in the abrasive powder used, including the size, shape, hardness, and chemistry of the particles and their interaction with the substrate.[6-14]

There are a large number of available commercial air-abrasion units, and each can be used at various settings with different powder admix mechanisms. Therefore, in order to improve the comparability of air-abrasion studies and their clinical use, it is important to study the PFR. In addition, water shrouding the powder stream has been introduced in some units to reduce atmospheric powder scattering. The consequence of this modification on air-abrasion cutting efficiency has not been studied previously.

Using alumina powder as an abrasive can lead to undesirable clinical over-preparation of dental hard tissues.[6,13,15,16] Therefore, with the purpose of promoting air-abrasion cutting tissues selectively to meet the MID paradigm, bio-active glass (BAG) powder has been introduced with the hope that practitioners can benefit from its properties, including its antibacterial effects, remineralization potential, and its potential to remove selectively more softened diseased or damaged tooth structures.[17-21]

In order to use air-abrasion appropriately, this study assessed the effect of certain parameters on BAG air-abrasion cutting efficiency/pattern using an enamel analogue, Macor, in simulated clinical conditions, compared to conventional 27-μm alumina air-abrasion (the positive control). The abrasion assessment was preceded by a PFR study of two different intraoral air-abrasion units using different powder-air admix mechanisms.

The three null hypotheses investigated in this study were

1. There is no effect of air pressure on powder flow rate in either Aquacut or Air-Flow Master air-abrasion units.
2. Operating parameters have no effect on the cutting efficiency/pattern on an artificial enamel analogue.
3. There are no differences in the cutting efficiency between alumina and BAG powders when used under standardized clinical conditions.

MATERIALS AND METHODS

Characterization of the abrasive powders' surface topography and elemental composition were determined using scanning electron microscopy-energy dispersive x-ray spectroscopy (SEM-EDX, accelerating voltage of 25 kV, working distance of 13 mm). Particle size analysis was carried out using a laser diffraction particle analyzer (Cilas, Orleans, France), and the results were analyzed with the Particle Size Expert software package (Cilas).

The nozzle output air pressure of the air-abrasion unit was measured using a digital pressure indicator (DPI 705, Druck, UK) attached to the output nozzle. The nozzle diameter was validated using a digital measurement device (Quadra-Check 300). Periodic calibration of output pressure and the nozzle diameter was conducted throughout the experiments to ensure consistency and standardization under all experimental conditions.

PFR Evaluation

Comparing the weight of a collecting container, including a layer of sponge and a paper filter, before and after one minute of active air-abrasion permitted the study of PFR.[22] The powder reservoir was consistently refilled with the abrasive powder to a predetermined line, and the powder was manually stirred prior to use throughout.

In order to investigate the effect of air pressure on PFR on both Aquacut (Velopex, Harlesden, UK) and Air-Flow Master (EMS, Nyon, Switzerland) air-abrasion units, the powder feed dial was fixed at the middle setting and the air pressure was adjusted into 40, 60, and 80 psi. Ten measurements were conducted within each experimental group using BAG powder.

The same method was used to calculate the PFR (g/min) for each of the powder feed dial settings—1, 3, and 5—used as a variable during cutting efficiency/pattern assessment using the Aquacut unit (nozzle output internal diameter 600 μm). This experiment was conducted by fixing the air pressure at a constant 60 psi.

Cutting Efficiency/Pattern Assessment

The dynamic abrasion procedure was performed within a plastic chamber attached to high vacuum suction using a micropositioning device to fix the nozzle and a stage to move the substrate. A Macor sheet (50×50×5 mm) was located on the stage attached to a moving coil actuator (SMAC, Crowley, UK), programmed to obtain 10-mm linear movement at a velocity of 0.5 mm/s.

The variables assessed in this study were air pressure (20, 40, and 60 psi), powder feed dial value (1, 3, and 5), nozzle angle (45° and 90°), nozzle distance (1, 2, and 5 mm), and the cutting mode (dry and wet) for both alumina and BAG powders. When each variable was investigated, the remaining parameters were fixed as follows: air pressure, 60 psi; powder feed dial, 3; nozzle angle, 90°; nozzle distance, 2 mm. Ten troughs were made in each experimental group.

Evaluation of the effect of different parameters was conducted using dry air-abrasion mode. However, to evaluate the influence of shrouding the air-powder stream with a water curtain on the cutting efficiency, a disposable plastic tip, used to mix the air stream with water, was attached to the tip of the nozzle.

Using proprietary measurement control software (STAGES, TaiCaan Technologies Ltd, Southampton, UK), a standard scan area of 5 × 2 mm was chosen over the central region of each trough. Optical white light confocal profilometry (Xyris 4000 WL, TaiCaan Technologies) was used to image the surface topography of the resulting 200 troughs. The white light sensor had a 0.01-μm resolution, a spot size of 7 μm, and a gauge range of 350 μm. The scan was performed with a 10-μm step-over distance in medium precision measurement mode.

The resulting three-dimensional (3D) topographic data sets were analyzed using MountainsMap surface analysis software (Version 6.2.6332, SARL Digital Surf, Besançon, France) to obtain the volume of the troughs (mm^3). A macro was written to read and analyze the 3D data automatically using the "measure volume of a hole" function. Air-abrasion cutting efficiency was established by comparing the volume removed with the assumption that the settings were more efficient when air-abrasion removed a greater volume of Macor. Representative 3D selected images from BAG powder groups were examined to characterize the cutting pattern.

The statistical analysis was conducted using the SPSS Statistical Package (version 19.0, SPSS Inc/IBM, Chicago, IL, USA). One-way analysis of variance (ANOVA) and Bonferroni *post hoc* testing was performed to analyze the PFR data, and repeated-measures ANOVA followed by Bonferroni *post hoc* test was used for the analysis of the cutting efficiency assessment data. The level of statistical significance was established at $p=0.05$ for both tests.

RESULTS

The alumina powder had an angular shape, while BAG powder had an aspect ratio of 1:1, with some angular edges seen on the particle surface (Figure 1). The compositions of alumina and BAG powder are shown in Figure 2. The particle size distribution percentiles (10%, 50%, and 90%) of the alumina powder were 23, 37, and 51 μm, respectively, while those of BAG powder were 23, 56, and 82 μm, respectively.

PFR Evaluation

PFR mean values (±standard deviations) regarding the effect of air pressure on PFR are shown in Figure 3. Air pressure had no effect on the PFR in the Aquacut unit, which showed constant PFR for all air pressure values. In contrast, increasing the air pressure in the Air-Flow Master® unit from 40 and 60 psi to 80 psi increased the PFR in a statistically significant manner ($p<0.001$, $p=0.01$, respectively).

PFR ranges for the Aquacut unit settings involved in this study for both powders are shown in Figure 4. The PFR increased significantly when the powder feed dial was adjusted from the minimum to the

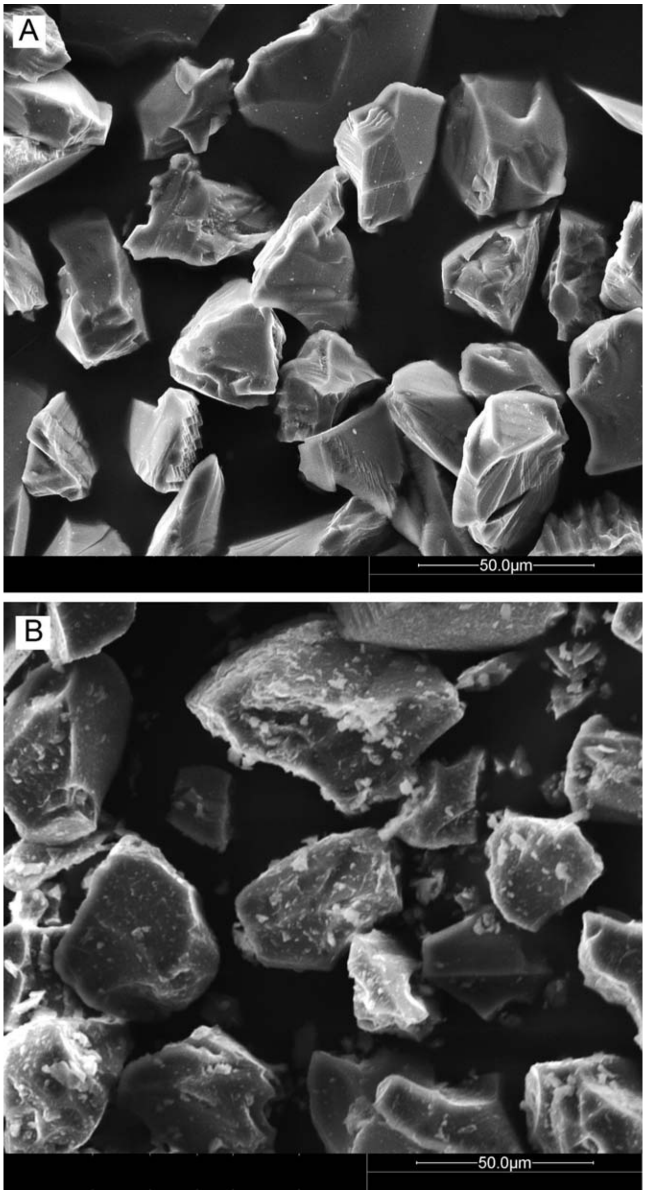

Figure 1. *(A) SEM of alumina particles; (B) SEM of BAG particles (accelerating voltage: 25 kV; working distance: 13 mm; magnification: 1500). Alumina powder exhibits an angular shape, while BAG powder has an aspect ratio of 1:1, with some angular edges seen on the particles.*

maximum value within the BAG powder groups ($p<0.001$).

Cutting Efficiency/Pattern Assessment

An increase in air pressure resulted in an increase in Macor volume removal in both powder groups. With alumina, the increase was not different statistically between the 40 and 60 psi values, while it was significant within BAG groups, which showed statistical differences among all the air pressures tested

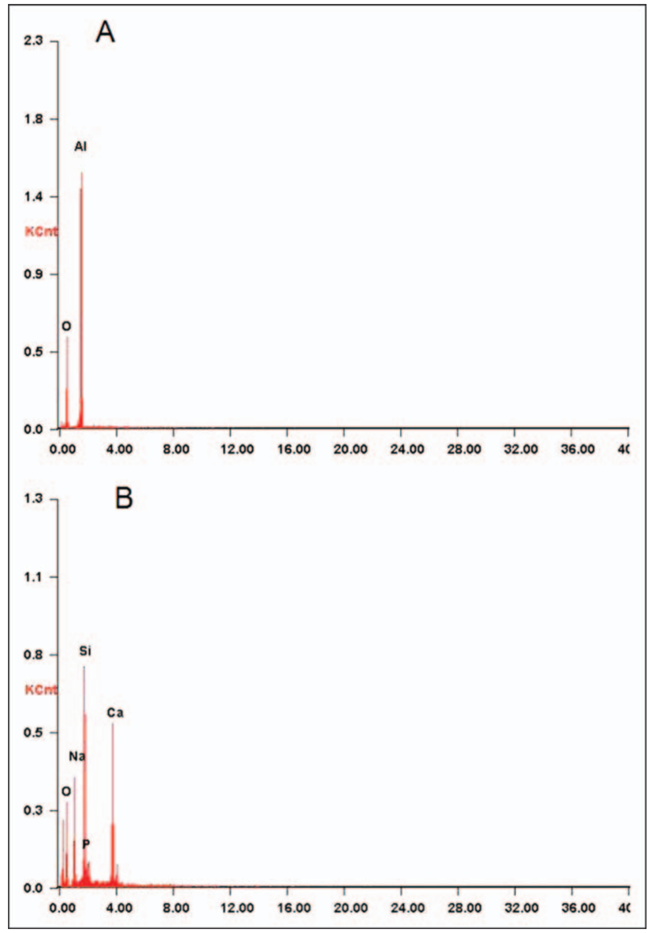

Figure 2. *(A) EDX revealed aluminium and oxygen peaks in alumina powder; (B) EDX revealed silicon, calcium, phosphorus, sodium, and oxygen peaks in BAG powder (accelerating voltage: 25 kV; working distance: 13 mm).*

($p<0.001$). The volume of material removed when the air pressure was fixed at 20 psi was 0.75 ± 0.16 mm^3 (mean ± standard deviation) in the alumina group, whereas 60%, statistically less, was removed in the BAG group (0.3 ± 0.02 mm^3; $p=0.01$). However, the difference in the Macor volume removed between the two powders was not statistically significant and declined to 30% (1.39 ± 0.33 mm^3) in the alumina group and 0.97 ± 0.04 mm^3 in the BAG group when the overall air pressure was increased to 60 psi.

Adjusting the powder feed dial to the highest value increased the volume of Macor removed ($p<0.001$, $p=0.005$ in alumina and BAG groups, respectively) (Figure 5). In addition, increasing the nozzle-substrate distance from 1 to 5 mm improved air-abrasion cutting efficiency ($p<0.001$) (Figure 6). Setting the PFR to the lowest value caused more pronounced fluctuation in the base of the trough

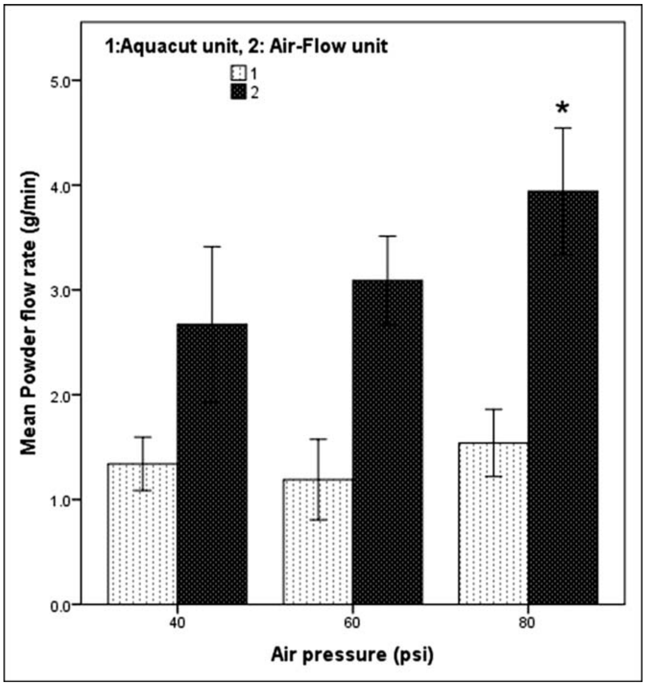

Figure 3. *PFR mean value ± standard deviation (SD) (g/min) correlated with variable air pressures (powder feed rate dial setting fixed at middle values). *Indicates statistically significant differences between air pressure at 40/60 psi and 80 psi in Air-Flow Master unit (*$p < 0.05$*).*

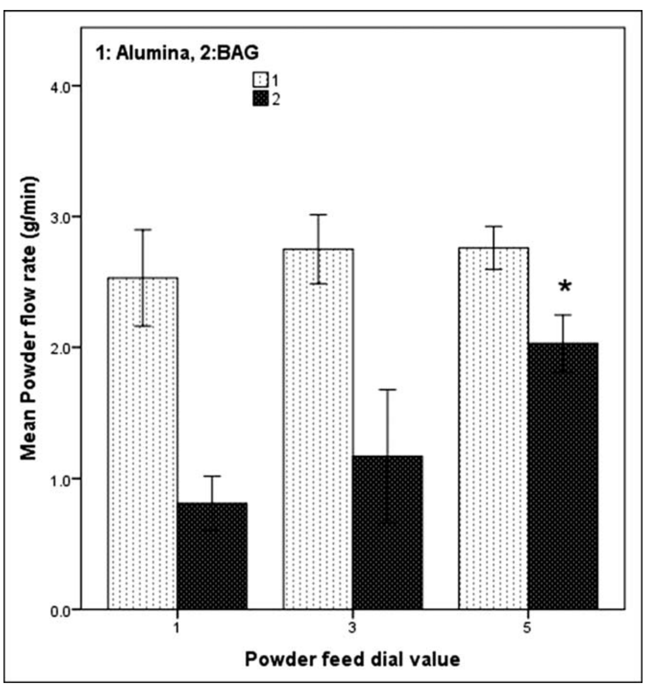

Figure 4. *PFR mean value ± standard deviation (SD) (g/min) for alumina and BAG powders correlated with variable powder feed rate settings (air pressure fixed at 60 psi). *Indicates statistically significant differences between powder feed rate dials 1 and 5 within BAG powder group (*$p < 0.05$*).*

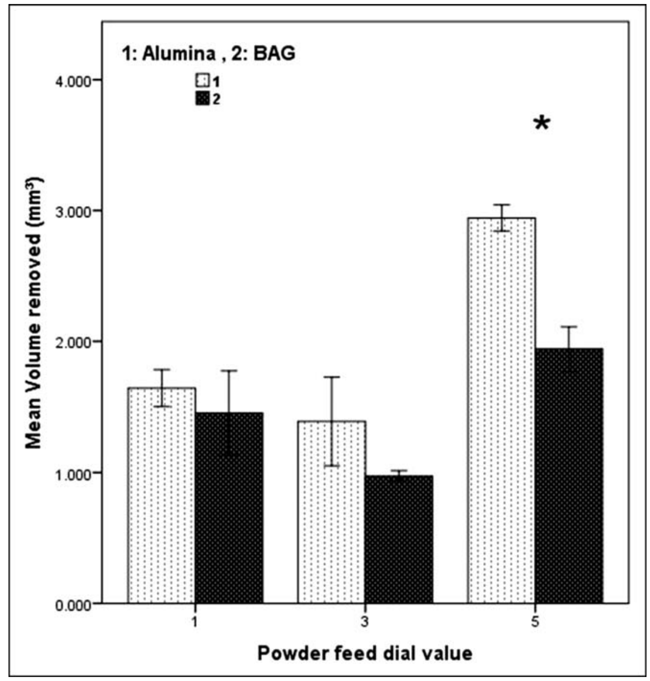

Figure 5. *Macor volume removed mean ± standard deviation (SD) for alumina and BAG groups correlated with variable powder feed rate dial settings. *Indicates statistically significant differences between powder feed rate dials 1/3 and 5 in both powder groups (*$p < 0.05$*).*

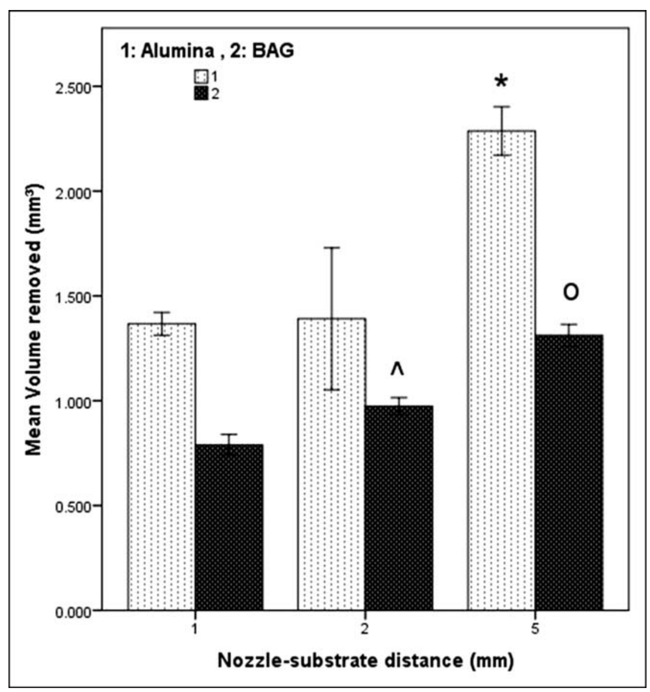

Figure 6. *Macor volume removed mean ± standard deviation (SD) for alumina and BAG groups correlated with variable nozzle-substrate distance. *Statistically significant differences between distances of 1/2 and 5 mm in alumina groups; ^Statistically significant differences between distances of 1 and 2 mm in BAG groups; °Statistically significant differences between distances of 1/2 and 5 mm in BAG groups (*$p < 0.05$*).*

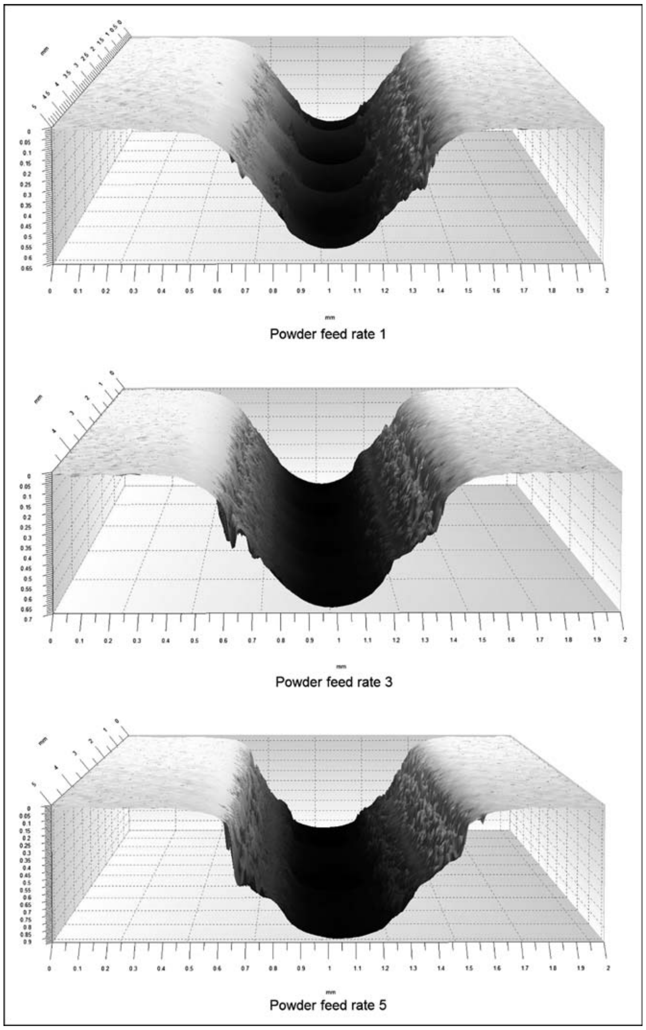

Figure 7. *3D scans of selected, representative BAG air-abrasion troughs. (A) The fluctuation in the base of the trough when powder feed dial was set at 1. (B and C) Troughs prepared using powder feed dial 3 and 5, respectively.*

along its length (Figure 7). The nozzle distance of 5 mm produced more rounded trough margins compared to those produced with shorter distances (Figure 8).

Statistically significantly more Macor was removed when the air-abrasion nozzle was fixed at 45° (2.52 ± 0.14 mm^3 and 1.76 ± 0.08 mm^3 within alumina and BAG, respectively) rather than 90° (1.39 ± 0.33 mm^3 and 0.97 ± 0.04 mm^3 within alumina and BAG, respectively) ($p<0.001$). The shape of the troughs varied according to the nozzle angle: 45° produced a trough with a "V" cross-section, while 90° presented troughs with a "U"-shaped cross section (Figure 9).

There was no significant difference in the cutting efficiency between dry and wet air-abrasion systems

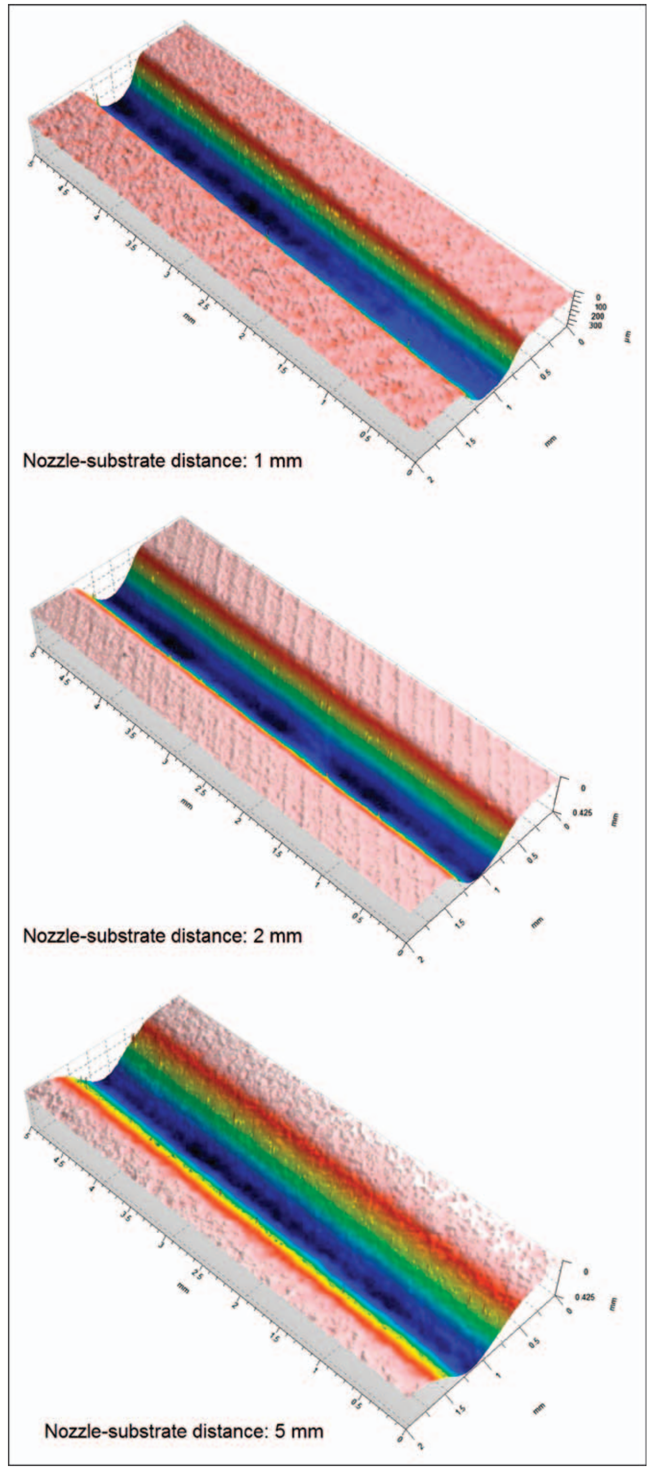

Figure 8. *Trough margin variation according to the nozzle-substrate distance within BAG powder group. Nozzle-substrate distance of 5 mm (C) results in a rounded, less well-defined trough margin compared to nozzle-substrate distances of 1 mm (A) and 2 mm (B).*

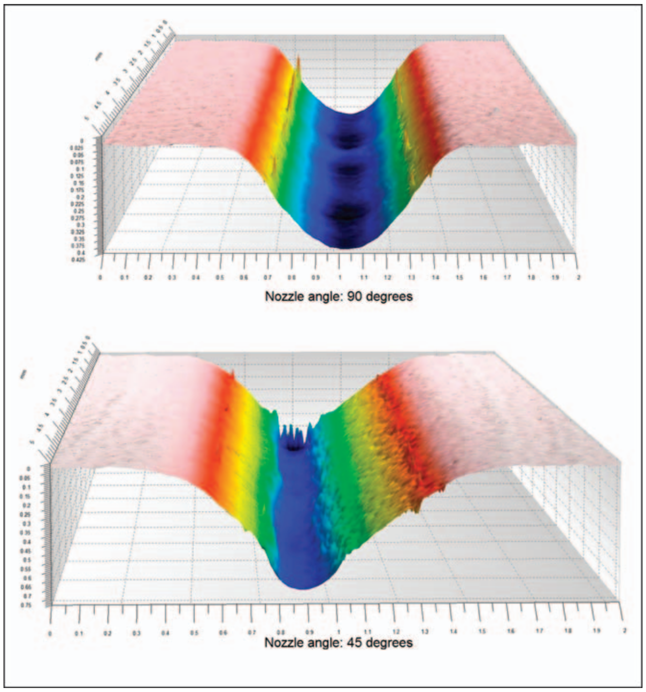

Figure 9. *Representative scans revealed the cross-sectional trough shape difference between the 90° nozzle angle (trough with "U" cross section) (A) and 45° nozzle angle (trough with "V" cross section) (B) within BAG powder groups.*

for both powders. In alumina groups, dry air-abrasion removed 3.36 ± 0.17 mm^3 and wet air-abrasion removed 3.49 ± 0.48 mm^3. The Macor volume removed in the BAG groups was 1.84 ± 0.34 mm^3 and 1.93 ± 0.61 mm^3 using dry and wet abrasion, respectively.

DISCUSSION

The two air-abrasion units employed in this study use different mechanisms to admix the abrasive powder with the air propellant stream. The Aquacut unit uses a vibration mechanism to admix the abrasive particles with the air stream, and this explains why a constant PFR was recorded regardless of the air pressure values. However, in the Air-flow unit, in which an air vortex is created inside the powder chamber, air pressure not only modifies the particles velocity but it also alters the amount of expelled powder from the nozzle. PFR measurement (g/min) for the powder feed dial values during air-abrasion studies makes the results obtained using a specific air-abrasion unit comparable and reproducible using different air-abrasion units when the PFR is equilibrated to the same ranges. BAG powder exhibits different bulk density, atmospheric moisture uptake, and particle size/shape when compared to alumina, which in turn explains the variation in their flowability. Therefore, it is advised that BAG powder should be manually stirred in the reservoir prior to the abrasion procedure to help prevent the separation of the different particle sizes, which will affect the flow rate and, therefore, cutting efficiency.

Macor was used as the control substrate, as it has been used for assessing the cutting rate and efficiency of operative technologies in dentistry as a result of its consistent, uniform hardness, which is not found in human enamel, as the enamel hardness varies from person to person according to the individual's food consumption and is depth-dependent within the same tooth as a result of histological heterogeneity.[23,24] Using Macor sheets also provided a reliable, flat surface as a target for air-abrasion cutting and subsequent objective analysis using optical surface profilometry, which was used in the present study to determine the volume of material removed, as it is considered an accurate method by which to measure hard tissue loss.[25,26]

Assessing the dynamic cutting efficiency has the advantage over static cutting, as it mimics more realistically the clinical situation, in which the procedure is accomplished by moving the nozzle over the target substrate.

The findings of this study indicate that there is an increase in the air-abrasion cutting rate for both powders when air pressure increases. Since the increase in air pressure does not increase the PFR in the Aquacut unit, as proved in the PFR evaluation study, this finding may be explained based on the dependency upon the increased kinetic energy of the particles, a finding consistent with those of previous studies.[7,27] It is important to be aware that when low air pressure was applied, the difference in air-abrasion cutting efficiency between the two powders more than doubled, implying that at low air pressure settings, the cutting efficiency of air-abrasion depends mainly on the nature of the abrasive powder rather than on the physics of air-abrasion unit itself.

The finding concerning the effect of PFR on the cutting efficiency is inconsistent with the findings of a previous study,[14] which claimed that an increase in PFR without a concomitant increase in the air pressure is pointless. In the present study, employing both a dynamic cutting protocol and high vacuum suction reduced the surface choking of particles when excessive quantities of abrasive were applied. The undulating troughs resulting from using less powder may be caused by the irregular distribution of particles within the air stream. Most of the particles are concentrated into a small portion of the stream's cross-sectional area.[28]

Previous studies[9,29] indicated an inverse relationship between the distance and the cutting efficiency. In those studies, the researchers used the cross-sectional views of the cut surfaces to assess the cutting efficiency, whereas in this experiment the whole volume removed was calculated using the 3D measurement methodology.

When the nozzle was fixed at 45°, the percentage of the air stream's peripheral portion, which presents a reduced concentration of particles with reduced velocity,[10] increased, and that in turn produced cross-sectional "V"-shaped troughs.

The air-abrasion operating parameters controlling the nozzle position affected significantly the cutting efficiency observed in both powder groups. This can be explained by the fact that increasing the distance and fixing the nozzle at 45° reduced the surface choking of particles, which is assumed to disturb negatively the propellant stream.

One of the objectives in this study was to determine the difference in cutting efficiency between alumina and BAG powders. It was noticeable that alumina powder removed considerably more material than did BAG powder. In addition, the cutting efficiency was more controllable within BAG powder groups since only slight differences in operating parameters altered the cutting efficiency, while alumina powder groups demanded considerable alterations in the parameters to exhibit statistical differences in the cutting rate. The abrasive powders consisted of different shapes, particle size distributions, and hardnesses,[13,30] which may explain the variations observed in this study of cutting efficiency and sensitivity to the operating parameters.

CONCLUSIONS

The three null hypotheses investigated were rejected. Using air-abrasion should be preceded by system calibration to identify the factors affecting the abrasive powder propulsion, as they differ according to the unit's design. Vibration admix units exhibited a constant powder flow rate regardless of air pressure. However, it is advocated that practitioners check the BAG powder condition within the powder chamber before the abrasion procedures to obtain a sufficient powder flow rate. Manufacturers need to take note and provide this information clearly to clinicians. Air-abrasion cutting efficiency is more conservative and controllable when BAG powder is used as an abrasive powder, encouraging its role in minimally invasive operative dentistry.

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Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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