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An *In-vitro* Investigation of the Effects of Variable Operating Parameters on Alumina Air-abrasion Cutting Characteristics

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Clinical Relevance

Changing air-abrasion operating parameters has an effect on the cutting rate and, ultimately, the depth and shape of cavities produced in Macor (an enamel analogue).

SUMMARY

Air-abrasion is a tooth preparation technology developed in the 1940s that is currently gaining popularity due to its compatibility with adhesive restorations. Variables, including propellant pressure, powder flow rate, nozzle angle and distance to the tooth surface abrasion time, can affect the cutting rate of the air-abrasion unit. A static setup and a more clinically realistic dynamic experimental setup have been used to assess the effect of these parameters of the cutting rate on an enamel analogue. By keeping each parameter fixed, its effect on the cutting rate was examined. The results showed that increasing the propellant pressure (20-100 PSI) caused an almost linear increase in the cutting rate in both setups. Increasing the powder flow rate (0.5 – 3 g/minute) concurrently increased the powder flow and caused an increase in the cutting rate but with a plateau differing for the different propellant pressures. The nozzle angles producing the highest cutting rates were 60° and 75° for static and dynamic cutting, respectively, with smaller and larger angles producing lower rates. Increasing abrasion time in static cutting and the nozzle advancement rate in dynamic cutting both caused an increase in the cutting rate. These findings are relevant for both clinicians,

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who might wish to alter the cutting rate of their instrument, and researchers, who should always control the numerous parameters in studies involving air-abrasion in order to control the variables, which can influence the end effect of air-abrasion.

Table 1: *List of Air-abrasion Operating Parameters and Their Control*

Parameter	Ability to Control in Use
Distance of nozzle to target	Continuously adjusted during clinical operation
Angle of nozzle to target	
Time of abrasion	
Propellant Pressure	Adjustable by user in most units
Powder flow rate	
Nozzle shape and size	Particular to every unit/manufacturer
Abrasive powder	
Propellant	Limited
Target	None

INTRODUCTION

Air-abrasion is an operative technique used clinically for the preparation of teeth since its invention by Black in 1945.[1] The original air-abrasion (Airdent) unit was developed as an alternative to the slow-speed handpieces of the day, utilizing the kinetic energy of abrasive particles dispersed in a high pressure fluid air stream. The particles cut the tooth by impacting on it at high speed and high kinetic energy, thereby causing fracture of the surface. Publications followed that described and discussed its clinical use and the effects of air-abrasion on dentin and enamel.[2-8] A 30-year gap in air-abrasion research then followed, primarily caused by the introduction of the high-speed turbine. Air-abrasion research saw a rebirth in the mid-1980s, because of its use in prophylaxis and due to the development of adhesive plastic restorative materials whose cavity requirements are more suited to those produced by air-abrasion (rounded cavity walls and high energy, roughened surfaces). There are a number of fundamental questions that remain unanswered, however, relating to the influence of variable operating parameters/settings to the cutting characteristics of the abrasive jet. The answers to these questions constitute knowledge equivalent to that of dental rotary instruments that a dentist acquires, relating to the cutting efficiency on variations of the application of pressure, the rate of revolution or the use of different burs (diamond grit size, flute number and design etc). There is a need for the clinical and research operator to have an understanding of the effect of these parameters, because they affect the manner and effectiveness by which the tooth tissue is abraded. Alteration of the operative settings during the air-abrasion procedure can offer a means of further control of the technology. There are several operating parameters or variables that influence the cutting characteristics of air-abrasion (Table 1) and little knowledge has been reported on how these quantifiably influence the cutting of tooth tissue despite air-abrasion being in clinical use for more than half a century. Studies have investigated the effect of nozzle tip design,[9] the profile of the cavities in deciduous teeth[10] and the cavosurface margin geometry in permanent teeth.[11] Interestingly, the most comprehensive report to date comes from Black's original paper,[2] where he comments on the effect of increasing the distance of the nozzle tip from the tooth surface. There is a gap in current knowledge as to how the operating parameters influence the cutting of enamel, which this study sets out to investigate.

Enamel is a heterogeneous tissue with variable physical properties both between different teeth and within a tooth. In order to improve the reproducibility of gathered data when abrading enamel, there is need for a standardized enamel substitute. Macor, a 55% fluorophlogopite mica and 45% borosilicate machinable glass ceramic, has been successfully used as an enamel substitute in rotary instrument cutting studies.[12-13] The cutting patterns produced were found to be similar to those in enamel. Thus, the current study investigated the effect of varying propellant air-pressure, abrasive powder flow rate, abrasive size, nozzle to substrate angle and distance on the cutting rate and profiles produced during the static and dynamic cutting of an enamel substitute. The null hypothesis investigated was that there would be no differences in the cutting rate and cavity profiles produced when varying the above parameters.

METHODS AND MATERIALS

A commercially available air-abrasion unit (Abradent, Crystalmark, CA, USA), with a straight custom-made tungsten carbide-tipped round cross-section nozzle (0.8 mm internal diameter), was used in the current study. The abrasive was aluminum oxide angular particles (27 µm, Crystalmark). Macor (Radio Spares, UK) was used as the enamel analogue in the form of a flat, 6 mm-thick sheet. Compressed air from the hospital centralized air supply, dried using an in-line due-point suppressor, was used. Compared with the smaller bell chambers of portable/surgery compressors, the larger volume bell chamber of the centralized supply led to immeasurable air-pressure variations. Air-pressure was controlled and measured using the built-in regulator valve and analogue manometer. After choosing a pressure setting, the pre-selected air pressure was confirmed with a manometer reading through the air-abrasion unit's output tubing; in all instances, both readings

Table 2: *A table of the variables used in both static and dynamic cutting experimental procedures, showing the values of each variable which was investigated in the same row as the variable name. The values in bold represent the values used unless otherwise indicated. Ten cuts per variable were produced for this study.*

Variable Parameters	Variable Values Tested					
Air Pressure (psi)	20	40	**60**	80	100	
Powder Flow rate (g/min)	0.5	1	1.5	**2**	2.5	3
Nozzle distance (mm)	1	2	**3**	4	5	6
Nozzle angle (o)	45	60	75	**90**		
Time (sec) (static cutting)	5	**10**	15	20	25	30
Advancement rate (mm/sec) (dynamic cutting)	0.125	0.25	**0.5**	1	1.5	2

were in agreement. The powder flow rate of the air-abrasion unit was controlled by an analogue switch graded from one to ten tenths. Calibration of the analogue powder flow settings was carried out in g/minutes by collecting the spent powder over a timed period in a container of known weight, which was subsequently weighed. To control for variations in powder output, the powder chamber was filled to a marked line (standard, constant volume) prior to abrasion of each of the samples.

Static Cutting

The air-abrasion nozzle was clamped at the chosen predetermined angle and distance from the substrate and it remained static for the duration of the abrasion procedure. The variables shown in Table 2 were used to produce 10 abrasion cavities in the Macor sheet for each of the parameter settings, producing a total of 260 abrasion cavities on the flat Macor surface. The amount of material removed was gravimetrically assessed prior to and after abrasion of each cavity. As Macor is a uniform material of known density ($2.52 gcm^{-3}$), the volume of material removed was derived using $V=\Delta M/\rho$(V=volume, ΔM=change in mass, ρ=density). A non-contact profilometer (UBM Masstechnik GmbH, Ettlingen, Germany) was used to scan the cavity shape produced and the accompanying software used to analyze the shapes.

Dynamic Cutting

In an attempt to mimic clinical operating conditions but still allow for fine control of the variables, a relative movement between the nozzle and the Macor was introduced by mounting the enamel analogue on a stage whose linear movement was controlled by means of a programmable moving coil actuator (SMAC, Horesham, UK). A dust containment and evacuation chamber was constructed, which housed both the stage and a micro-positioning device, allowing the control of distance and angle at which the nozzle was fixed relative to the target. The powder flow rate and air pressure were controlled as described previously, while a 10 mm linear movement of various velocities was programmed into the moving coil actuator. The variables and their values used are shown in Table 2. A total of 260 troughs, 10 per variable, were abraded on the flat Macor surface, ensuring a spacing of 2 mm between the edges of each abraded trough. A contact profilometer (Triclone, Renishaw, Gloucestershire, UK) was used to scan the Macor surface using a 500 µm diameter ruby stylus. The step-over distance was 50 µm and the probe deflection was set to 0.3 to avoid the stylus skipping over the roughened ceramic surface. After surface scanning, the Macor sheet was cut using a water-cooled rotary diamond blade (LabCut, Agar Scientific, Stansted, UK) to ensure that the concavity of the abraded trough floor could accommodate the 500 µm diameter probe and maintain a single point contact. The information was exported in stereolithic (.stl) file format to a surface measurement software (TrueMap, TrueGage, PA, USA). The rate of material removal was calculated by measuring the area defined between the profile of the trough in a cross-section taken at right angles to the long axis and the plane of the Macor surface. The area of the trough was calculated in 10 equispaced sites in the central 6 mm of the 10 mm trough using the 2D profile utility on a magnified segment of the surface measuring 12x12 mm. Ten points placed in line on either side of the trough on the unprepared surface were used to define a least-squares plane to represent the flat Macor surface.

A one-way analysis of variance (ANOVA) was used to compare the effect of variables on the removal rate. The SPSS v14 statistical package was used to perform the statistical calculations (α=0.05).

RESULTS

The results are summarized in Figures 1 through 4 and Tables 3 and 4. In the static cutting, there was an increase in cutting efficiency when the nozzle-substrate distance was increased. The largest increase for all powder flow rates was when the nozzle distance was increased from 2 to 3 mm. A less pronounced increase was seen in the dynamic cutting.

Changing the angle of the nozzle also had an effect on the rate of Macor removal. In static cutting, 60 degrees offered the highest rate of removal, while 75 degrees showed the highest cutting rate in dynamic cutting.

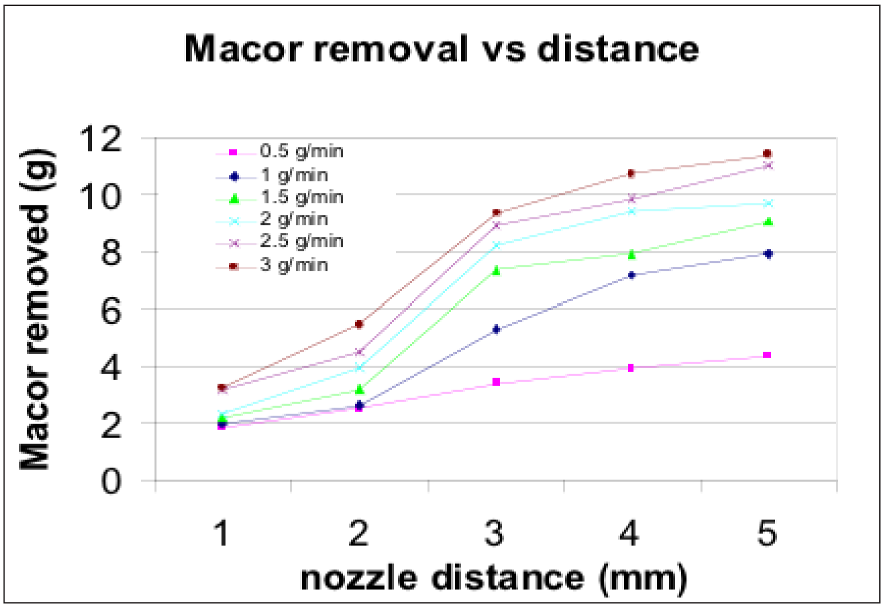

Figure 1. *Graph showing the amount of Macor removed using alumina air-abrasion in 10 seconds (nozzle angle of 90°/air pressure of 60 psi). All results within the series are significant (α=0.05).*

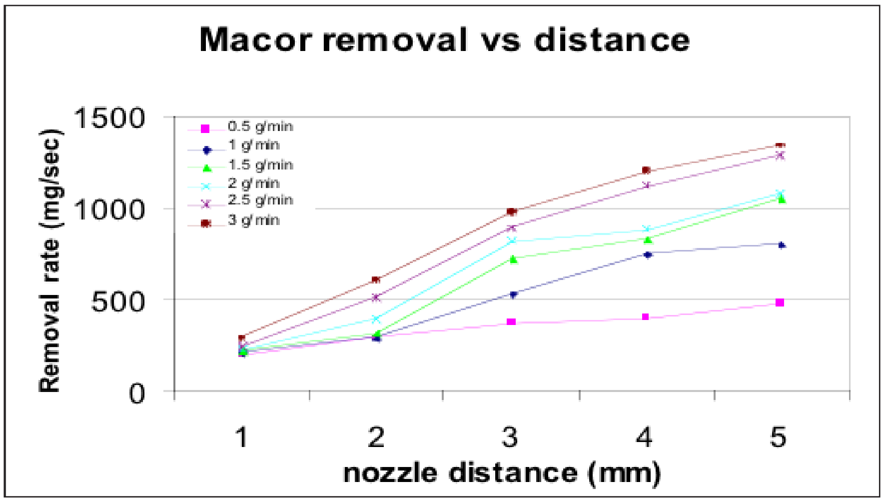

Figure 2. *Graph showing the rate of Macor removal using alumina air-abrasion in 10 seconds (nozzle angle of 90° and air pressure of 60 psi). All results, except nozzle distance 1 and 2 for 0.5 g/minute, are significant (α=0.05).*

There was, however, no statistical difference between these two nozzle angles in either static or dynamic cutting.

The effect of abrasion time did have a significant effect on the amount of Macor removed during static cutting. Increasing the advancement rate in dynamic cutting also produced a significant increase in the rate of Macor removal.

It was observed that, during dynamic cutting, as the relative movement of the nozzle against the Macor began, a V-shaped trough margin developed. This V-shaped trough margin was far more pronounced as higher propellant pressures were employed.

DISCUSSION

The results disprove the null hypothesis showing variation of the cutting rate and cavity shape. The current study has shown how operating parameters affect the cutting rate and efficiency of the enamel analogue Macor. The practical application of these findings is in the clinical use of air-abrasion, where efficiency can be increased and, therefore, clinical time reduced and greater control can be exerted over the shaping of the cavity created. The method of assessment of cutting is very important in order to mimic clinical performance. Static and dynamic cutting assessment carried out in this study highlight the difference between the two reported methods by showing the difference in the results obtained. It is the authors' opinion that the principle difference between the two methods is that, in static cutting, the spent powder and propellant exhaust through the cavity they have just created against the abrasion stream, thereby slowing down cutting efficiency. In dynamic cutting, the spent powder and propellant exhausts toward the side of the abraded cavity. The V-shaped trough margin effect, described above, is due to this side exhausting, as seen in dynamic cutting.

The findings from both the static and dynamic cutting experiments contrast with the findings of Bailey and Philips,[4] who found an inverse relationship between the nozzle distance and cutting efficiency. This might be due to the fact that Dolomite, their investigated abrasive, was intrinsically a softer material and was of a smaller particle size and might therefore require a higher speed of impact to carry the necessary momentum to damage the tooth surface. All abrasive particles decelerate after leaving the nozzle; the velocity decrease, however, might have left the particles in the Bailey and Philips study below their critical momentum, thereby decreasing the cutting efficiency reported. The substantial increase that was seen in cutting efficiency when the distance was increased from 2 to 3 mm in static cutting but not dynamic cutting is thought to result from exhausting of the gasses as described above. The finding that efficiency increases by increasing the nozzle to target distance from 1 through to 5 mm implies that the clinician has to, perhaps counter-intuitively, increase the distance of the nozzle to the enamel in order to cut faster. This, however, happens at the expense of cutting accuracy, as increasing the distance produces a more rounded cavosurface angle. The linear increase in cutting efficiency with increasing propellant pressure in both static and dynamic cutting is due to the fact that the propellant stream, and therefore the abrasive particles carried with it, travel at a higher speed and therefore with higher kinetic energy. The higher energy abrasive stream cuts the target by chipping it more quickly.

Increasing the powder flow rate (the amount of abrasive) without increasing the propellant pressure (the abrasive carriage capacity and speed) did not significantly increase cutting efficiency. Such an increase would result in creating more powder dust in the surgery without a noticeable improvement in clinical effect. When using one of the many adjustable air-abrasion units, the clinician has to avoid the temptation to set the powder flow rate to maximum. Although it is impossible to recommend settings for all the air-abrasion units available, the clinician is invited to think of the following concept when setting up the air-abrasion unit: The abrasives have to be accelerated to a certain velocity before they can result in chipping (cutting) of the enamel. The propellant jet has a "carrier capacity" that is increased by increasing the propellant pressure, resulting in higher propellant volume throughput as well as propellant velocity. Increasing the amount of powder in the stream without increasing the "carrier capacity" is pointless.

The effect of nozzle angle to the target on cutting efficiency is thought to be due to the manner in which the spent powder and propellant exhausts and its interaction with the abrasive stream. For the most efficient cutting of a flat surface, the nozzle should be held at 60 degrees. The effect of abrasion time did have a significant effect on the amount of

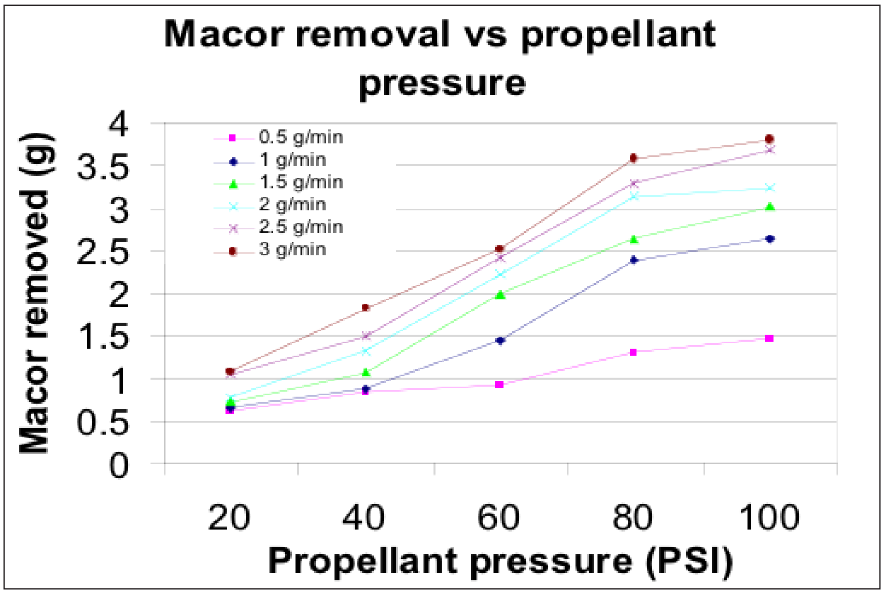

Figure 3. *Graph showing the amount of Macor removed using alumina air-abrasion in 10 seconds during static cutting (nozzle angle of 90° and nozzle to target distance of 3 mm). All results, except propellant pressure 40 and 60 for 0.5 g/minute are significant (α=0.05).*

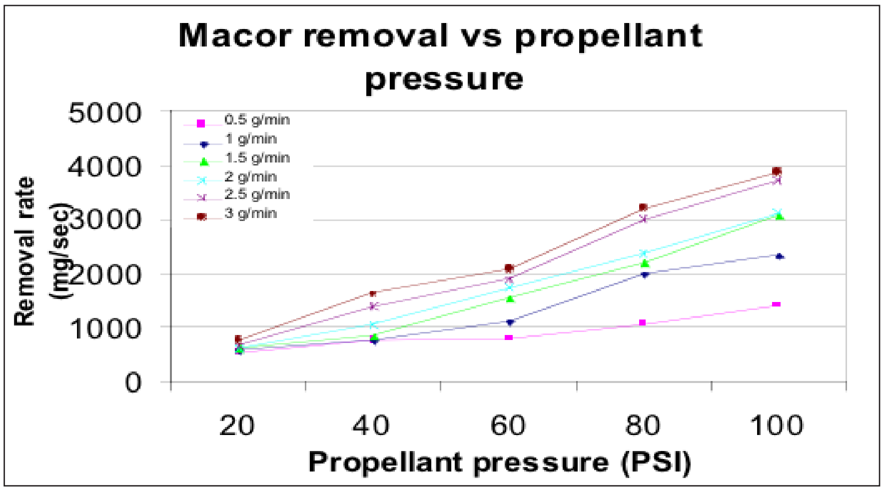

Figure 4. *Graph showing the rate of macor removeal using alumina air-abrasion during dynamic cutting (nozzle angle of 90° and nozzle to target distance of 3 mm). All results, except propellant pressure 20, 40 and 60 for 0.5 g/minute, are significant (α=0.05).*

Table 3: *Table showing the amount of material removed, as weight for static cutting and removal rate for dynamic cutting, for four different nozzle-to-target angles. For both types of cutting, the differences between the weights of material removed were significant within the series with the exception of 60° and 75° with respect to one another (α=0.05).*

	Static Cutting		Dynamic Cutting	
Angle	**Weight**	**SD**	**Rate**	**SD**
(°)	**(g)**		**(mg min^{-1})**	
45	5.96	0.48	600	25
60	11.18	0.59	1058	29
75	10.53	0.64	1072	33
90	8.2	0.61	820	39

Table 4: *Table showing the weight of material removed.* ***A****: static cutting—shows increasing weight of material removed with increasing abrasion time.* ***B****: Dynamic cutting—shows increasing rate of material removed with increasing advancement rate. All results significant within the respective series (α=0.05).*

A: Static Cutting			B: Dynamic Cutting		
Time	Weight	SD	Adv Rate	Rate	SD
(s)	(g)		(mm sec^{-1})	(mg min^{-1})	
5	4.96	0.32	0.125	766	27
10	8.2	0.62	0.25	790	35
15	12.83	0.87	0.5	821	39
20	14.39	0.89	1	847	39
25	16.91	1.43	1.5	889	43
30	17.56	1.37	2	918	48

Macor removed, in contrast to the conclusions of Peruchi and others[10] on deciduous teeth.

CONCLUSIONS

The current study has quantified the effect of different air-abrasion operating parameters on the cutting rate and efficiency of the air-abrasion unit on a standardized enamel analogue. The findings are useful both for the operative dentist and researchers; research in air-abrasion has to be performed with strict control of the operating parameters in order to minimize the variables. A previous publication has outlined the importance of the volume of powder present in the reservoir before and during the air-abrasion procedure and the potential changes in powder flow rates if this is altered.[14] Although the clinical use of air-abrasion is far removed from the tightly controlled conditions of the current study, knowledge of the cavosurface angles produced and how the increase in powder flows does not always proportionally increase the cutting rate, for example, have a practical benefit. Should the clinician wish to achieve the highest cutting rate, the suggested setting would be to hold the nozzle at 60 degrees and 5 mm away from the enamel surface, set the propellant pressure to maximum and the powder flow rate to 2.5g/minute. For the last setting, it is important for the clinician to liaise with the manufacturer for this information. Some marketed air-abrasion units can have powder flow rates that are significantly higher than this. However, it is worth noting that equivalent cutting rates can be produced by reducing the powder and increasing the propellant pressure, effectively allowing fewer, but higher energy particles, to do the cutting.

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