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Controllable Jet Injection of Dental Local Anaesthetic

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ABSTRACT Objective: Fear of dental procedures is a common barrier to effective dental care. A promising technique to overcome dental anxiety is needle-free jet injection, which involves delivering local anaesthetic as a high-speed jet capable of penetrating the oral mucosa without a needle. Previous efforts have used loud, uncontrolled injectors designed for transdermal delivery that have failed to achieve significant uptake in dental practice. Methods: In this work, we present and validate a controllable jet injection device driven by a silent electric motor for the delivery of dental local anaesthetic. The injector includes a novel tubular attachment at its distal end, which allows the delivery to be performed comfortably throughout the mouth. The expected pressure loss resulting from the use of this attachment is analysed. This analysis predicted that a 75 mm long tubular attachment of 0.53 mm radius would result in negligible pressure loss. To validate delivery in human tissue, the injection system was used to perform 18 injections into the mouths of two Thiel-embalmed human cadavers. These injections were visualised using cone-beam computed tomography (CBCT). Results: Benchtop testing of the prototype injector verified the expected pressure loss along the attachment. The CBCT scans demonstrated that the fluid was successfully delivered to the desired locations, adjacent to the root apex of the teeth, at every injection site. Conclusion: These outcomes validate the performance of this novel needle-free injector, demonstrating its potential as a tool to reduce dental anxiety.

INDEX TERMS Needle-free, jet injection, dental anxiety, control, anaesthetic, local, Lidocaine, cone-beam computed tomography.

Clinical and Translational Impact Statement— Our controllable jet injection device overcomes key limitations associated with previous attempts to deliver dental local anaesthetic needle-free. This could greatly reduce barriers to effective dental care.

I. INTRODUCTION

Anxiety or fear of dental procedures is a common barrier to safe and effective dental care [1]–[3]. This issue is estimated to affect 9 % of the population [4]. Dental anxiety often arises from negative experiences with dental practice; ironically, it is the delivery of anaesthetic, which is meant to make the process painless, that causes the greatest anxiety [1], [2]. This is possibly related to needle phobia, which has been found to be prevalent in over 20 % of young adults [5]. Dental anxiety has also been associated with avoidance of care [1], which can lead to more expensive and risky treatments subsequently being required.

One method that has been trialled to reduce dental anxiety is the use of needle-free jet injection systems. This technique involves delivering local anaesthetic as a high speed jet, which is capable of penetrating the oral tissue without a needle. Recently, jet injection has been more commonly applied to deliver vaccines and protein-based drugs through the skin, but it has also been applied to the delivery of local dental anaesthetic [6], [7]. In the 1970s, the Syrijet [8] and Panjet [9] jet injection systems were explored as an anaesthetic delivery method to reduce dental anxiety. These devices resulted in successful anaesthesia of the target tissue, and were claimed to improve patient comfort [9], [10]. More recently, jet injection systems such as the Madajet [11], [12], Injex [13]–[15], and Comfort-in [16] have been applied to the delivery of dental anaesthetic. Rather than developing a purpose built device for dentistry these more recent jet injection systems have typically used devices also marketed for a range of other medical applications. This may have contributed to the mixed results found when evaluating patient preference for these systems [11]–[14]. Despite these efforts needle-based local anaesthetic delivery still remains the 'gold standard' practice.

The jet injection systems that have been trialled for the delivery of dental local anaesthetic have all been driven by an uncontrollable energy source, such as the release of a compressed spring [8], [12], [16]. Recently, focus in the field of jet injection has moved to controllable devices driven by electric motors [17], piezoelectric actuators [18], laser-induced cavitation[19], [20], or controlled pneumatic sources [21]. These injectors are able to develop a wide range of precisely-controlled fluid pressures and are capable of adjusting pressure dynamically during the injection. This approach allows the injection outcomes such as depth of penetration and volume delivered to be precisely controlled. This also means a single injection device could provide a platform delivery technology that can perform a wide range of different injections. Such control has not yet been applied to the jet injection of dental local anaesthetic. This control over needle-free delivery has some similarities to needle-based controlled delivery devices, which have increased in popularity in the field of dental anaesthesia over the last decade [22]

A controllable jet injector would allow the dental practitioner to control delivery outcomes, and adjust these between successive injections [18], [23]. Such a device could also allow the jet speed or volume of delivery to be minimised where possible, to maximize the comfort of the patient. In contrast, the spring-based injectors recently reported in dental anaesthetic delivery trials have often simply used devices and injection parameters appropriate for delivery through skin. As well as being highly controllable, motor driven jet injectors offer the key advantage of being silent [17]. A recent study using a spring based injector for dental anaesthetic delivery found the 'pop' sound inherent to a spring-injector was a major issue for patients [14].

Jet injectors typically expel the fluid jet in-line with the movement of the driving mechanism, which works well for transdermal drug delivery, but can lead to difficulty in positioning the device appropriately in confined spaces such as the mouth. It is uncommon for jet injection devices to include bends, or long, thin sections in the fluid channel, as these characteristics are often associated with pressure losses that reduce injector performance. However, if an injection attachment could be produced that allowed injections to be comfortably performed within the mouth, it could significantly improve the uptake of this technology. This would have significant potential not just in dental delivery applications but also lead to the possibility of jet injection being used in other internal applications such as during laparoscopy or endoscopy.

The current best practice for the delivery of local anaesthetic in dentistry can involve either an infiltration, where delivery is targeted to just the relevant tooth, or a nerve block, where delivery is targeted to a large nerve bundle servicing a wide area of the mouth and face [24]. While a single controllable jet injection device may be capable of both types of injection, it is sensible to first evaluate this technology when performing an infiltration. Previous dental anaesthetic jet injection studies have focussed on infiltration [12]. During an infiltration the target delivery site for the anaesthetic is adjacent to the bone surrounding the root apex of the tooth [24]. The anaesthetic then diffuses through the thin plate of cortical bone and anaesthetises the nerve endings in the area of deposition, generating pulpal anaesthesia.

In this work, we investigate the effectiveness of a jet injection device driven by a voice-coil actuator with a long, tubular injection attachment for the delivery of dental local anaesthetic. The attachment was designed to facilitate easy and comfortable placement within the oral cavity. The expected pressure loss associated with the tubular attachment was analysed to inform the design and construction of a prototype injection system. The effectiveness of the attachment, and the overall performance of the device, were characterised by measuring the flow rate of the jet. Cone beam computed tomography (CBCT) scans were used to evaluate the ability of this device to deliver anaesthetic in cadaveric tissue. This delivery was intended to target the same area of the oral tissue as a traditional, needle based, infiltration.

II. FLUID ANALYSIS

To make jet injection a comfortable, easy, and repeatable procedure in dentistry, we propose the addition of a long, slender tubular attachment at the front of the device. This will allow injections to be performed throughout the oral cavity while keeping the bulk of the device outside the mouth. Toward this aim we first sought to compute the expected pressure loss in such a tubular injector attachment as a function of the tube radius. This analysis was performed assuming a jet speed (v_j) of 150 m/s was required through an orifice with a radius (r_O) of 100 μm at the end of a 75 mm long tube attachment. A length of 75 mm was chosen as this matched that of similar dental tools that can reach the back of the mouth. Piston radius and stroke were chosen based on a standard 0.3 mL jet

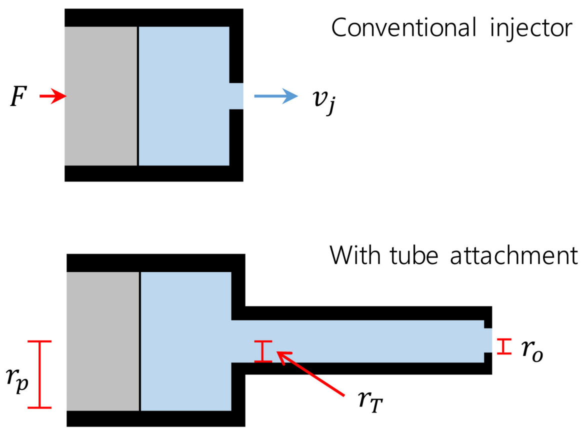

FIGURE 1. Diagram indicating the geometry of a conventional jet injector, and one with an additional tube attachment. We evaluate the expected pressure loss as the tube radius (r_T) is varied from that of the orifice (r_O) to that of the piston (r_P).

injection ampoule ($r_P = 1.75$ mm, $L = 30$ mm). The injected fluid was assumed to be water.

In our analysis, the radius of the tubular attachment (r_T) was varied between the radius of the piston and that of the orifice; these geometric parameters are depicted in Fig. 1.

To evaluate the pressure loss along the tube we must first calculate the Reynolds number

$$Re = \frac{\rho u D_H}{\mu} = \frac{2r_O^2 v_j \rho}{\mu r_T}, \quad (1)$$

where ρ is the density, and μ the viscosity, of water. Fig. 2 shows the Reynolds number calculated over the range of r_T (from r_O to r_P). This demonstrates how the flow through the tube varies from laminar to completely turbulent over this range of tube radii.

With laminar flow (Re < 2300) Poiseuille's Law provides an analytical expression for the pressure loss along the length of the tube:

$$\Delta P = \frac{8\mu LQ}{\pi r^4} = \frac{32\mu L v_j r_O^2}{4r_T^4}. \quad (2)$$

In completely turbulent flow (Re > 10000) the Moody Chart defines a series of semi-empirical relationships which can be used to predict the pressure loss along the pipe. The Moody Chart has been shown to be consistently accurate to within 15% of experimental data [25]. Swamee and Jain presented an explicit relation for pressure loss in turbulent flow that can be used to compute the values represented in the moody chart without iteration:

$$\Delta P = \frac{1.07\rho QL}{(2r_T)^5}\left(ln\left[\frac{\varepsilon}{7.4r_T} + 4.62\left(\frac{2vr_T}{Q}\right)^{0.9}\right]\right)^{-2}. \quad (3)$$

The flow rate in the tube (Q) and the average fluid velocity in the tube (v) can be determined by the chosen jet speed ($v_j = 150$ m/s) and orifice radius ($r_O = 100\ \mu$m) [17]. ε is the surface roughness; we have used a value of 0.5 μm (representing stainless steel with a '2B' finish). While there is no precise method to characterise the pressure loss in transitional flows ($2300 < Re < 10000$), it is reasonable to expect that it will be between the values predicted by the turbulent and laminar estimates. Fig. 2A shows equations 2 & 3 used to estimate the total pressure loss along the tube attachment as a function of tube radius. Both equations 2 & 3 are computed for Reynolds numbers between 2300 and 10000, and in this zone the pressure loss cannot be predicted more precisely than to expect that it should lie within the range bounded by equations 2 & 3.

In addition to the pressure loss along the length of the tube, represented by equations 2 & 3, there will be some minor losses caused by the bend in the tube and the sharp pipe inlet [25]. The minor losses can be calculated based on the fluid velocity in the tube (v) and the loss coefficient (K_L) associated with each of the features using:

$$\Delta P = \frac{K_L v^2}{2g} \quad (4)$$

where g is earth's gravitational constant. Values for K_L of 0.4 and 0.8 were selected for the bend and inlet, respectively [25]. The sum of these minor losses, shown in Fig. 2A, is around four orders of magnitude lower than the pressure loss due to the tube itself, so can be considered negligible in this application.

As a pressure difference in excess of 12 MPa is required across the orifice to achieve a jet speed of 150 m/s, most of the losses represented in Fig. 2A can be considered negligible. It is only as the tube radius approaches the size of the orifice itself that the predicted loss is >1 MPa and would have a significant impact on the development of the jet. The line indicating turbulent loss is not shown for pressure losses >12 MPa; above this point over half of the pressure developed by the piston would be lost along the length of the tube when generating a jet travelling at 150 m/s.

Examining only the pressure loss suggests that the tube radius should be as large as possible. The cost of a larger tube radius is an increased dead volume in the ampoule. The dead volume DV is plotted against the tube radius in Fig. 2B. This was calculated as simply the volume of the tube,

$$DV = \pi r_T^2 L. \quad (5)$$

Increasing dead volume increases the amount of drug that is wasted in order to achieve an injection. Fig. 2B demonstrates that the dead volume of the jet injection system becomes greater than the injectable volume (300 μL) when the tube radius is greater than 1.13 mm.

Assuming the device could be repeatably filled (and refilled), a dead volume on this scale may not be a significant problem, but it would be preferable that this be minimised, ideally well below the injectable volume. In current practise dentists deliver anaesthetic from ∼2 mL vials where it is common for a large proportion (>500 μL) to be unused, and subsequently discarded.

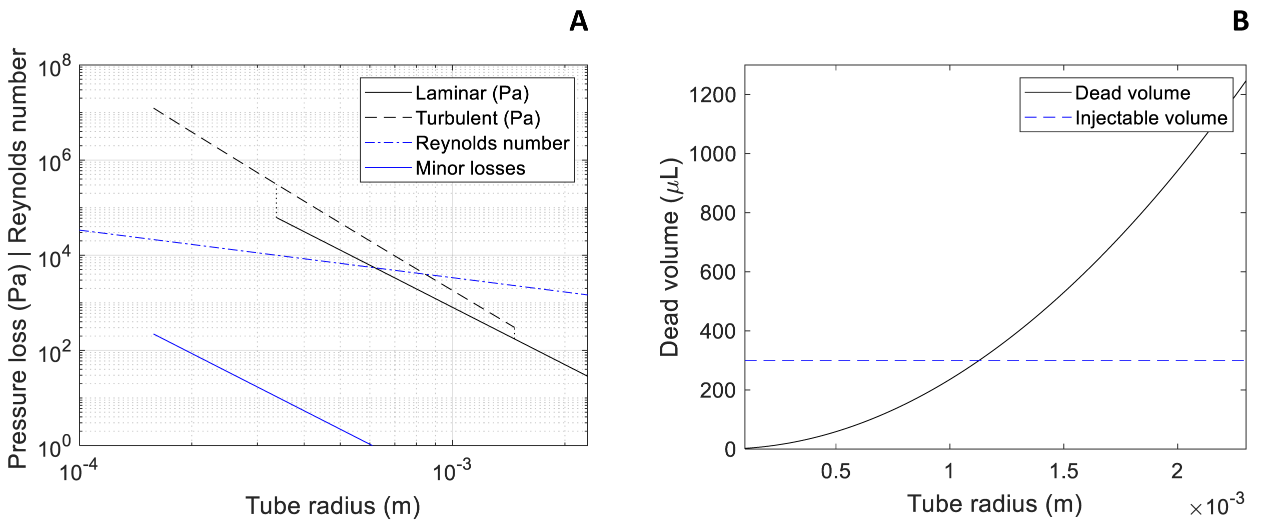

FIGURE 2. **Left: Predicted pressure loss along the length of the injection attachment assuming laminar flow (solid) and turbulent flow (dashed). The turbulent line extends to a maximum pressure loss of 12 MPa, when half of the pressure generated by the piston would be lost in the wand when generating a 150 m/s jet. Right: Dead volume within the tube attachment.**

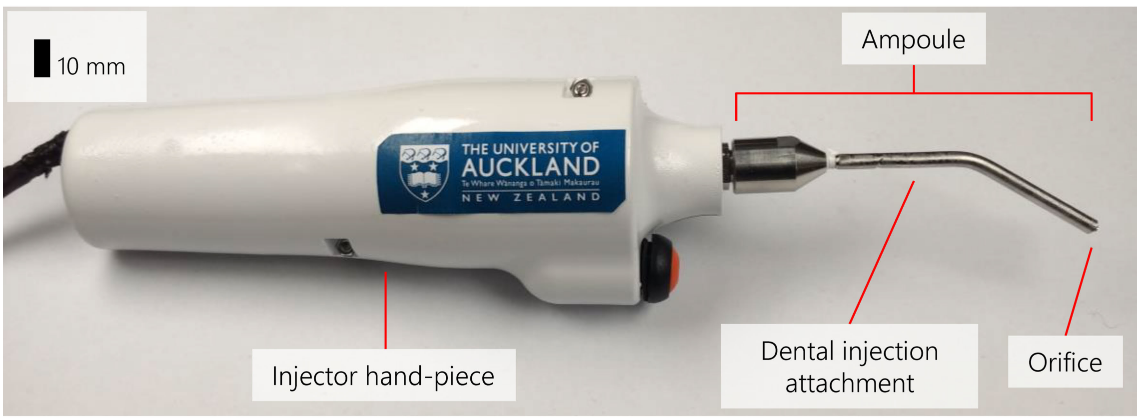

FIGURE 3. **Dental jet injection device and its components. A 3D-printed case serves as the hand-piece and houses the voice coil motor which drives the injection.**

III. MATERIALS AND METHODS

The previous analysis demonstrates that there exists a range of tube radii for which the expected pressure loss is negligible and the dead volume is acceptably low. Based on this we proceeded to construct a prototype using a tube radius of 0.53 mm. Given this radius our analysis predicts a pressure loss of between 12 kPa and 50 kPa, and a dead volume of 65 μL.

A. INJECTION DEVICE

The jet injector used in this study (Fig. 3) is similar to that presented in [26]. This device was driven by a voice coil actuator with a stroke length of 30 mm, resistance of 4.6 Ω, and motor constant of 3.0 N/$\sqrt{}$W. The voice coil was rigidly connected to a stainless steel piston which moved within a custom stainless steel ampoule with a 3.57 mm diameter bore, giving the device a maximum deliverable volume of approximately 0.3 mL. This ampoule included a long, slender tube attachment with a 200 μm diameter orifice (O'Keefe Controls Co.) at its distal end, through which the fluid jet was formed. The position of the motor was measured using a potentiometer (RDC10, Alps Electric Co.), and a button positioned on the injector case was used to trigger the injections. The injector hand-piece had a total mass of approximately 400 g.

The driving voltage for the motor was delivered using a custom controller-amplifier, as presented in [27]. This system used capacitors to store the energy required for an injection, and controlled the power supplied to the motor using an H-bridge switched at a frequency of 20 kHz.

1) ATTACHMENT FOR DENTAL JET INJECTION

The injection device differed from the spring based injectors used in previous dental jet injection studies as it was driven by an electric motor, and it included a long, tubular dental attachment. The fluid channel within the attachment was a

17G hypodermic tube (1.07 mm ID, 1.47 mm OD). This tube was mounted within a larger, outer tube (1.80 mm ID, 3.95 mm OD) which allowed the attachment to be mounted into the injection device, and provided some structural support. This outer tube had a thread machined on the inner diameter of the distal end to allow the orifice to be screwed into place. This attachment was 75 mm long and had a 35 degree bend approximately half way down its length. This bend was chosen to match the form of other dental tools, such as the standard 3-in-1 air/water tips [28]. The internal volume of the attachment was 65 μL.

B. EXPERIMENTATION

1) DEVICE PERFORMANCE

Experiments with and without the attachment were performed to observe its effect on the production of the jet. Five step inputs of voltage (40 V, 60 V, 80 V, 100 V, and 120 V) were applied to the injector and the flow rate of the resulting jet was measured. These tests were repeated with and without the dental attachment in place, allowing a direct comparison with a standard jet injection nozzle with the same 200 μm diameter orifice. The volume flow rate through the orifice was estimated from the measurement of the piston position, by assuming conservation of volume.

To examine the repeatability of the injection device (including attachment) for a single injection type, a series of five injections were performed by applying a 100 V step input to the motor. The flow rate of the jet was estimated during these five injections based on the measured piston position, assuming conservation of volume.

2) EX VIVO INJECTIONS

Ethical approval for this research was obtained from the University of Otago Human Ethics committee (approval number H18/044). Two partly dentate cadaveric heads were used to evaluate the ability of the injection device to deliver fluid into human oral tissues. Specimens were preserved using the Thiel-embalming method to preserve the texture, elasticity, volume, colour, and shape of the soft tissues [29], [30].

A series of 18 jet injections were performed by injecting a 1:1 solution containing Lignocaine (Lidocaine hydrochloride 2%, Lignospan Special^{TM}, Ivoclar Vivadent) and an iodine-based contrast agent (Omnipaque^{TM}300 mg Iodine/mL, GE Healthcare). Injections were conducted by applying a 100 V pulse to the motor for 70 ms, producing injections of 0.22 mL at a mean volumetric jet speed of 110 m/s. As shown in Fig. 4, eight 0.22 mL injections were performed on Subject 1, with one injection delivered per site. Subject 2 received ten injections across five sites (Fig. 4), hence twice the volume of the solution was delivered at each site. When performing an injection the tip of the attachment was pressed against the gum such that the jet would penetrate perpendicular to the surface of the gum. At each injection site the delivery was targeted to an area adjacent to the root apex of the target tooth.

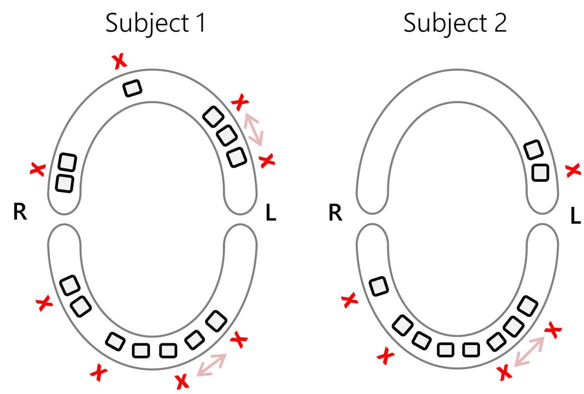

FIGURE 4. Schematic dental charting for each cadaveric head. The crosses indicate the injection sites. Contrast was observed at each of the delivery sites, the arrows indicate areas where the two adjacent injection clouds have overlapped.

To observe the location of the injected fluid, a cone beam computed tomography (CBCT) scanner (Orthophos XG 3D Ceph, Dentsply Sirona) operating at 85 kVp and 7 mA was used to obtain CBCT scans of the heads in full field of view mode (8 cm $\times$ 8.5 cm). Scans were visualised and processed using Sidexis 4 (Dentsply Sirona). The resulting 3D CT volumes were processed by manually adjusting the transparency and colour attributed to the voxels based on the opacity observed in the CBCT. This allowed us to visualise the anatomic features (teeth and bone) relative to any other areas of high opacity. A false colour scheme was added to highlight areas with greater opacity than bone with a red colour. Teeth and bone would typically be the most opaque features in an X-ray, and thus the presence of areas more opaque than teeth and bone indicate the injected contrast agent.

IV. RESULTS

A. DEVICE PERFORMANCE

Fig. 5 shows the two injections at 120 V, where the use of the attachment caused a slight reduction in volume flow rate (red dashes). In these injections, the mean jet speed with the attachment in place was 120 m/s, while with no attachment it was 122 m/s. The mean jet speed from the series of ten injections performed at 40 V – 120 V was 0.66 % $\pm$ 1.19 % lower with the attachment in place.

The five repeat injections conducted with a 100 V step input resulted in mean jet speeds ranging from 112.8 m/s to 113.3 m/s. The mean and standard deviation of jet speed over these the five injections was 113.1 m/s. $\pm$ 0.2 m/s, demonstrating the high level of repeatability.

B. EX VIVO INJECTION

There was no clear evidence of significant amounts of surface fluid or failed injections throughout the 18 injections performed on both subjects. A temporary mark/indentation was often observed where the device was in contact with the oral mucosa (Fig. 6). Results from the CBCT analysis

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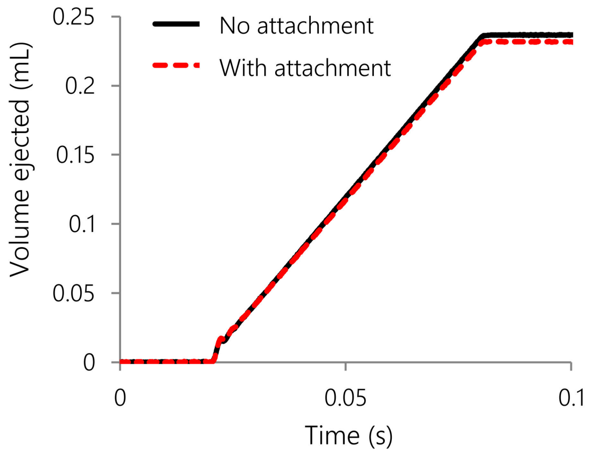

FIGURE 5. **The volume ejected from the jet injector (as implied by measurement of the motor position) during a 120 V step input applied to motor for a period of 60 ms, with and without the dental attachment.**

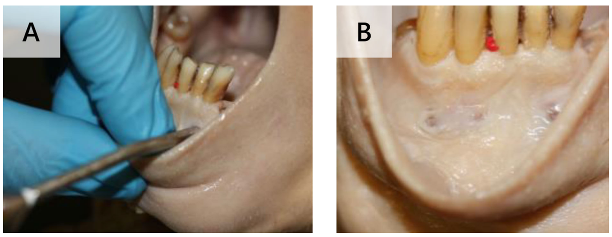

FIGURE 6. **Photos taken during the injections performed on Subject 1. A: The injection device in position to perform an injection. B: Anterior injection sites after three injections were performed. Contact marks can be observed at the sites where the injector was in contact with the gingiva.**

are summarised in Fig. 7. Radiopaque clouds of injected fluid were observed in both scans, the observation made at each of the injection sites is summarised in Fig. 4. At all 13 injection sites, radiopaque contrast clouds were evident, indicating the anaesthetic had been successfully delivered to all target locations. Adjacent contrast clouds appear to have overlapped at three locations (Fig. 4), creating ambiguity in identifying which injection deposited the anaesthetic in these regions.

V. DISCUSSION

The measurements of jet speed with and without the dental attachment tip demonstrated that use of the attachment was associated with a negligible increase in fluid resistance. This matches well with the initial fluid analysis that predicted a loss of just less than 50 kPa when developing pressures in excess of 12 MPa, representing a loss of less than 0.5 % of the pressure developed in the ampoule. This attachment allowed the device to be easily manoeuvrable and therefore support injections at any infiltration site throughout the oral cavity. This promising result highlights the scope for this technology to not only be effectively applied to dental anaesthetic delivery but also to other internal applications such as drug delivery during endoscopy or laparoscopy.

Medical-grade stainless steel was used for the prototype injection attachment. This material was chosen for its toughness, rigidity, and ability to be sterilised and reused. Given the high pressures (>10 MPa) associated with jet injection this attachment must be suitably rigid to prevent significant deformation during the delivery. This means a more expensive, re-sterilisable stainless steel tip would likely be preferable to a cheaper, single use attachment made from a plastic, such as polycarbonate.

The injections into the Thiel-embalmed human tissue demonstrated the injector was able to deliver the anaesthetic to the desired locations, adjacent to the roots of the teeth, at each of the intended sites. To our knowledge, this is the first time the location of jet injected fluid has been visualised in human oral tissue. Based on the location of the clouds of injected fluid observed in the CBCT scans, we would expect to have achieved anaesthesia of the target teeth. This is supported by previous reports of jet injected anaesthetic achieving anaesthesia of oral tissues [6], [8], [12], [16]. However, some local anaesthetic delivery studies have found jet injection to be associated with a different time course of anaesthesia relative to standard needle-based delivery. Two studies have observed the duration of anaesthesia to be reduced with jet injection [12], [16], while one of these also found the onset time to be shorter [16]. These contrast with findings from transdermal delivery studies that observed an increased onset time for jet injected anaesthetic relative to standard needle-based delivery [31], [32]. To evaluate the anaesthetic effect resulting from delivery with our device, and any associated discomfort, an in vivo clinical trial is required.

The contact marks observed at the injection sites (Fig. 6) suggest that future modifications of this device should include a way to soften this contact, perhaps similar to the silicone tips suggested by Saleh *et al.* [15]. It is possible, however, that these marks could be an artefact of the Thiel-embalming process (dehydration, for example), or simply due to the lack of peripheral blood flow and pressure in the cadaveric tissue. It will be important for future investigations to evaluate how to most comfortably contact the mucosa, as this has been found to be a key limitation in previous oral jet injection trials [15], [33].

The device used in this study differs from previous dental jet injectors as it is directly driven by an electric motor. This approach allows for real time control over the jet speed ejected from the device, and means that a single device can be used to target different depths, volumes, or adjusted between different patients. Motor driven jet injectors have only recently been developed to deliver up to 1 mL per injection, a volume comparable to that of spring or gas driven devices [34], [35]. Our results show that a motor driven injector enables dental anaesthetic delivery, even when presented with the additional resistance provided by the thin, tubular attachment.

The volume of anaesthetic required for infiltration is typically around 0.6 mL [36]. The device presented here has a maximum volume of 0.3 mL so would require two injections to achieve an infiltration. Changes to the ampoule or

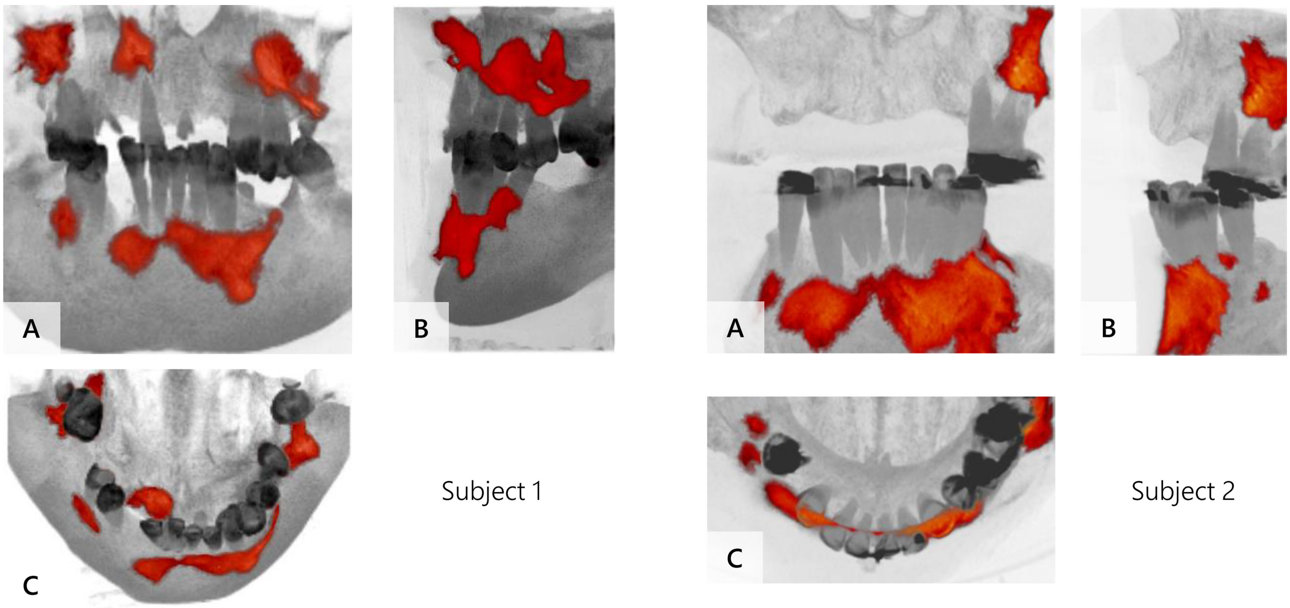

FIGURE 7. **CBCT reconstructions of both subjects following jet injection of the anaesthetic and contrast mixture. Locations of the delivered fluid are highlighted in red. A: Frontal view. B: Lateral view from the left of the subject. C: Occlusal view.**

motor used in our device could be made to accommodate sufficient volume to allow an infiltration to be performed in a single dose [34], [35], [37]. While it would be preferable to have the option of performing an infiltration in a single injection, it is likely that delivery over multiple injections may be beneficial for maximising patient comfort. Delivery over multiple injections would allow the anaesthetic effect from previous deliveries to reduce pain during injection, minimise pressure related discomfort, and support delivery on both sides of the tooth. Even if multiple injections are required, needle-free anaesthetic delivery with a controllable system has the potential to increase the speed and ease of infiltration for the practitioner, and improve the comfort of the patient.

Previous studies using spring-based jet injectors have had to use multiple injection ampoules in order to perform injections of different volumes [16], and these devices did not have the ability to adjust jet speed to target different depths. The flexibility provided by a controllable jet injection device gives the practitioner increased control over the depth and volume of anaesthetic delivery, as they are used to with needle-based delivery, which could lead to further improvements to patient comfort. However, it is not yet understood how the injection parameters may affect the resulting anaesthesia. The effects of the various injection parameters associated with the jet (speed, size, shape, and volume) have all been shown to affect injection outcomes in transdermal delivery studies [7], [23], [38]–[42]. The controllable injector presented here, designed specifically for dental anaesthetic delivery, provides a unique platform to systematically investigate the ideal jet speed and volume for jet delivery into oral tissue. This is an important area for further study.

Further experimentation should be conducted to evaluate whether the jet parameters can be controlled to improve the effectiveness of anaesthesia, and potentially allow a decreased volume of fluid to be delivered. The relationship between jet speed and penetration depth, and its consistency between patients, should also be the subject of further investigation. This would indicate the feasibility of a single needle-free device to conduct very different types of injections, for example, deep nerves blocks as well as shallow infiltrations.

VI. CONCLUSION

We have created a controllable, silent jet injection device for the delivery of dental local anaesthetic that can easily access injection sites throughout the mouth using a novel, slender injection attachment. Previous jet injection systems used in the oral cavity have not used a controllably driven device, nor an extended dental attachment. We have shown that the attachment adopted in this study introduced little additional fluid resistance or compliance, despite allowing the jet injection to occur 75 mm from the bulk of the device. The injection device was used to perform a series of 18 injections in the oral tissue of two Thiel-embalmed cadavers. CBCT imaging demonstrated that the anaesthetic was delivered to the desired locations, adjacent to the root apex of the teeth, at every observable injection site. Based on the locations of the injected fluid, we would expect to have achieved anaesthesia of the target teeth. These findings validate the performance of this system and provide a platform for future studies to assess the comfort and effectiveness of this technique in vivo as well as the effect of jet parameters on delivery into oral tissues.

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