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Effect of simulated intraosseous sinusoidal pressure on NaOCl extrusion

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ABSTRACT

Introduction: The present study examined the effects of irrigant flow rate and simulated intraosseous sinusoidal pressure on the rate of NaOCl extrusion from the apical terminus of a faux root canal.
Methods: An extrusion setup was designed to enable irrigant extrusion to be opposed by 30 mm Hg simulated intraosseous pressure. The faux canal apex was opposed by atmospheric + 30 mm Hg pressure (experimental) or atmospheric pressure only (control group). Using five irrigant delivery rates (15.6 8.0, 4.0, 3.4 or 3.0 mL/min), the extrusion rates of 2% NaOCl from the faux apex were measured in both groups (n = 16). Data were analysed with two-factor ANOVA and pairwise comparisons at $\alpha = 0.05$. Correlation between NaOCl delivery rates and extrusion rates in both groups were analysed with the Pearson product-moment procedure.
Result: Irrespective of the presence or absence of simulated sinusoidal pressure, NaOCl extrusion rates were positively-correlated with irrigant flow rates. For the factor "irrigant flow rates", significant differences in NaOCl extrusion rates were identified among all flow rates ($p < 0.05$), except for the pairwise comparison between 4.0 and 3.4 mL/min in the control. For all irrigant flow rates, NaOCl extrusion rate was significantly lower in the presence of 30 mm Hg simulated sinusoidal pressure than that obtained in the absence of opposing pressure ($p < 0.05$).
Conclusion: In the presence of 30 mm Hg simulated intraosseous pressure, NaOCl delivered via a side-vented needle inserted to 1 mm short of working length may be prevented from extrusion when its flow rate is ≤ 3.0 mL/min.
Clinical Significance: When opposed by intraosseous sinusoidal pressure, NaOCl delivered via a side-vented needle inserted to 1 mm short of working length may be prevented from extrusion when its flow rate is ≤ 3.0 mL/min.

1. Introduction

Debridement of root canals with sodium hypochlorite(NaOCl) carries the risk of periradicular extravasation of the extremely cytotoxic irrigant [1]. Following Becker's report of the sequela of accidental injection of NaOCl beyond the root apex [2], the literature is replete with case histories containing morbid photographs of NaOCl accidents [3–7]. All authors presage against using excessive delivery rates/pressure, or binding of irrigation needles to the canal space. However, the relationship between those anecdotal observations and the pathognomonic facial features associated with periradicular NaOCl extrusion has not been addressed.

Although intradermal injection of NaOCl may result in skin ulcerations [8], a recent report of a subject accidental infusion of NaOCl directly into the infraorbital tissues showed no signs of skin ulceration [9]. Surprisingly, the ecchymotic facial features [9] were virtually identical to those present in the 23 cases of root canal treatment-related NaOCl accidents compiled by Zhu et al. from the literature [10]. This serendipitous discovery prompted the authors to rationalise that NaOCl is ultimately drained into the anterior facial vein and its tributaries in a classical NaOCl accident [10]. Devastation of the superficial facial venous vasculature results in swelling and ecchymosis in the periorbital

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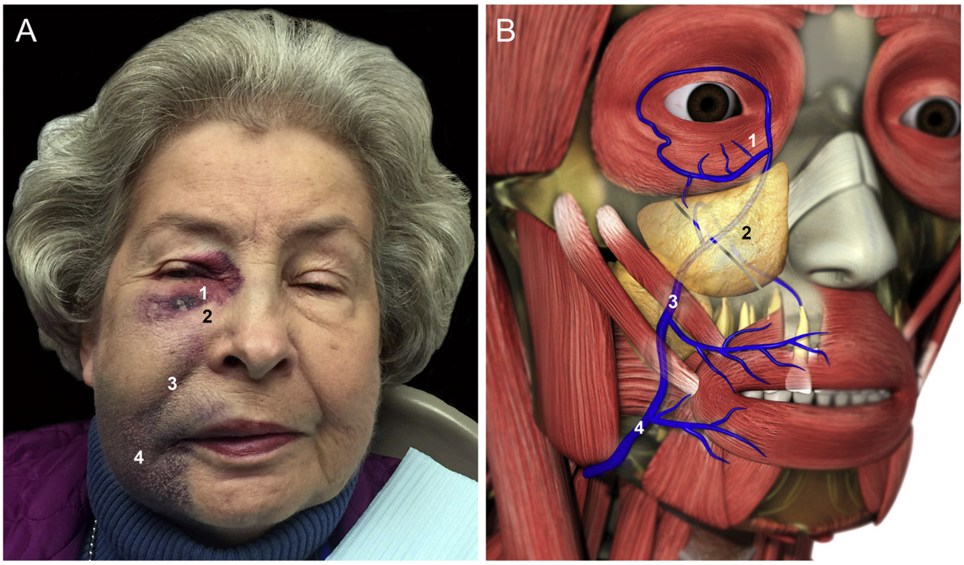

Fig. 1. A. Clinical photograph illustrating the pathognomonic manifestations of a NaOCl accident involving facial swelling and ecchymosis, and **B.** graphic dissection of the superficial venous vasculature along the course of the anterior facial vein and its tributaries. Damage to the anterior facial vein involves the superficial palpebral complex of the eyelids (area 1) that connects to the facial vein as it descends deep under the malar fat pad (area 2). The anterior facial and then arises superficial again at the level of the zygomatic muscles where it unites with the superior (area 3) and inferior (area 4) labial veins. The anterior facial vein continues superficially as it goes under the mandible and unites with the jugular vein. The superficial/deep spatial relationship of the facial venous system coincides exactly with the archetypical appearance of the subject who suffered from NaOCl extrusion during root canal treatment.

area, beneath the malar pad of fat that masks the ecchymosis, and at the angle of the mouth where ecchymosis reappears (Fig. 1). Although the most common course of venous drainage of teeth is the pterygoid plexus, a rare anatomical venous by-pass may cause the extruded NaOCl to be drained into the anterior facial vein [11]. The necessity for the presence of a venous by-pass explains why NaOCl accidents are rare [12,13], and that the facial ecchymosis resulting from extravasation NaOCl from the periapex is almost identical from case to case, irrespective of the tooth location [10].

Despite the presence of extensive facial swelling and ecchymosis, it remains elusive why contusion of the capillaries in the soft tissues around the root apex is never observed in all reported NaOCl accidents. Davies and Campbell asserted that the sinusoids in medullary bone is part of the non-collapsible component of the venous system, which may result in fatal air embolism when air is inadvertently introduced during surgical manipulation of the medullary bone [14]. This is in consonance with earlier reports that the intraosseous space is a non-collapsible vein [15]. Sinusoidal veins rapidly absorb fluids infused into the medullary areas because the sinusoidal blood pressure is only ~30 mm Hg [16,17]. Bone marrow injection is often used as a medium for administration of fluid directly to the venous system [18]. This physiologic background [10] accounts for the rapid onset of facial swelling/ecchymosis when NaOCl is expressed from the apical terminus into the central venous system.

For NaOCl to enter the sinusoids, the irrigant must have direct access to the sinusoids and be pressurised higher than 30 mm Hg to oppose the intraosseous sinusoidal pressure. A tooth surrounded by a healthy periodontal ligament prevents fluids from escaping the root canal system even if the apically-direct pressure is higher than 30 mm Hg. This combination of conditions, including the aforementioned rare venous by-pass, makes the NaOCl accident very rare. Although the likelihood of exacerbation of NaOCl has been examined for various clinically-relevant root canal instrumentation and irrigation parameters [19–28], no study to date has considered the effects of opposing intraosseous sinusoidal pressure on NaOCl extrusion from the root canal space.

When NaOCl extrusion was examined in a closed periradicular system versus an open system where there was no resistance to flow, the investigators opined that failure to consider partial apical resistance could have led to overestimation of NaOCl extrusion [29–31]. Accordingly, the objective of the present study was to examine the extrusion rate of 2% NaOCl when its delivery was opposed by simulated venous blood pressure in human sinusoids (~30 mm Hg). The null hypotheses tested were: 1) irrigant flow rate has no effect on the rate of NaOCl extrusion from the apical terminus, and 2) intraosseous sinusoidal pressure has no effect on reducing the extrusion of NaOCl delivered at different clinically-relevant flow rates.

2. Materials and methods

2.1. Model construction

A testing apparatus was designed with the objective of enabling irrigant extrusion to be opposed by 30 mm Hg to simulate the average intraosseous sinusoidal pressure. The set-up consisted of a single-rooted faux canal created within a polycarbonate block (McMaster-Carr, Santa Fe Springs, CA, USA). A 0.3 mm-diameter hole was drilled into the block to a depth of 19 mm. The final shape of the faux canal was completed by instrumenting the entire length with a size 30, 0.04 taper hand file. A 2 mm-diameter horizontal irrigant extrusion channel was drilled perpendicular to the faux canal, connecting the faux apical termination to a custom-made glass Extrusion Measurement Tube (EMT; Fig. 2A).

The faux canal was infused with 2% NaOCl, via a programmable precision pump (Legato 100; World Precision Instruments, Sarasota, FL, USA), through a 30-gauge Max-i-Probe side-vented needle (Dentsply Sirona, York, PA, USA) positioned 1 mm coronal to the canal's apical termination. Extruded NaOCl was directed into the left side of the EMT. Excess NaOCl was aspirated from the coronal access via an 18-gauge blunt needle attached to a dental operatory high vacuum unit (HiVac; Fig. 2A).

The EMT (~4.75 mm internal diameter with Luer fittings at both ends) was completely filled with water and an air bubble was used to isolate the extruded NaOCl coming from the left against the pressurised water on the right. The bubble also served as marker to record the volume of extruded NaOCl. The EMT was pressurised via a 3-way valve that could select either atmospheric pressure or a combination of atmospheric pressure and 30 mm Hg. Atmospheric pressure was realised by filling the open beaker with water and connecting it to the 3-way valve via a flexible tube.

A water column regulator was connected to a sealed reservoir (all components to the right of the 3-way valve; Fig. 2B) to achieve constant, precise 30 mm Hg pressure. A mechanical pressure regulator, attached to a compressed air cylinder, was used to deliver air at 5 psi. The air-flow rate was just strong enough to create constant bubbles at the bottom of a glass tube extending 406.4 mm (16 in.) into a column of water, enabling a stable, exact pressure of 30 mm Hg to be generated. The tubing was extended to the sealed reservoir to pressurize the water

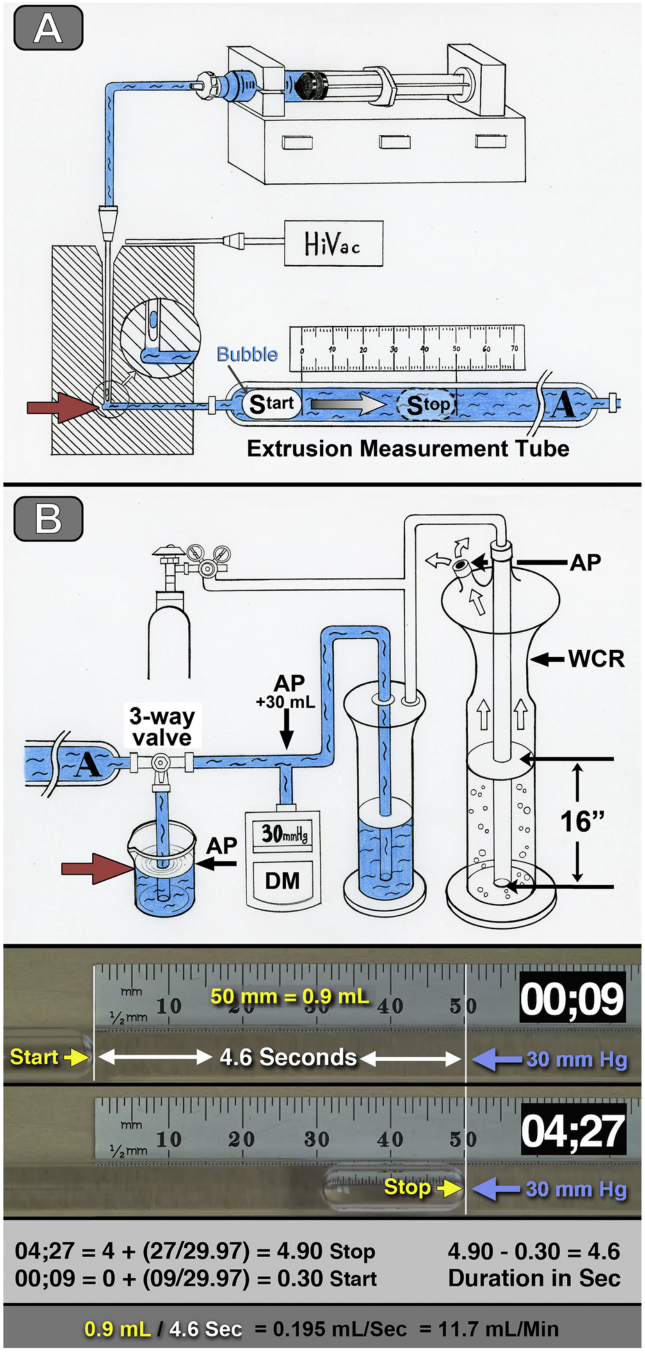

Fig. 2. A and **B**. Schematics of the experimental setup depicting irrigant delivery, NaOCl extrusion measurement and pressure control. Abbreviations: AP: atmospheric pressure; DM: digital manometer; WCH: water column regulator. **C**. Illustration of NaOCl extrusion measurement. A millimetre scale was placed directly above the Extrusion Measurement Tube. The air bubble in the top section surrounding the word “Start” was opposed by (atmospheric + 30 mm Hg) pressure. After positioning the bubble slightly to the left end of the mm scale, the video recorder and syringe pump were simultaneously activated. For video recording, time codes were recorded as the bubble passed the “Start” and “Stop” marks on the scale. A time code of 04;27 means that 4 s and 27 frames had elapsed. Conversion from NTSC time codes to time values is illustrated in the light area and the extrusion rate is calculated in the bottom line. In the present example, the bubble travelled 50 mm (0.9 mL) between the time codes 00;09 and 04;27. Hence, 0.9 mL of irrigant was extruded in 4.6 s, resulting in a NaOCl extrusion rate of 11.7 mL/min.

and drive it towards the right side of the EMT. A digital manometer was installed before the 3-way valve to monitor the pressure.

To avoid errant bubble movement, the EMT was levelled using a precision machinist level. The water level of the beaker (red arrow; Fig. 2B) was levelled with the apical termination (red arrow; Fig. 2A) to prevent the siphon effect. Extrusion of NaOCl from the faux apical terminus caused the air bubble to move from left to right. Extrusion rate was determined via the combined use of a millimetre scale and videography of the bubble movement.

Five irrigant flow rates were investigated: (1) 15.6 mL/min, representing the upper limit of a clinically-realistic flow rate [31,32]; (2) 3.4 mL/min, previously determined by the authors to be the safety threshold for positive-pressure irrigant delivery in a root canal system [10]; (3) 3.0 mL/min, a fast enough flow rate that is just below the safety threshold for positive-pressure irrigant delivery; (4) 4.0 mL/min, a flow rate that is just beyond the safety threshold for positive-pressure irrigant delivery; and (5) 8.0 mL/min, an empirically-logical flow rate between the lowest and highest flow rates. All irrigant flow rates were tested in two groups. The experimental group was tested using (atmospheric + 30 mm Hg) pressure, and the control group was tested using atmospheric pressure only.

The time elapsed during the course of NaOCl extrusion was calculated by converting the National Television System Committee (NTSC) time code (in frames/sec) to time values, from which the extrusion rate was determined (Fig. 2C; Supplementary video). Sixteen measurements were conducted for each of the 10 subgroups (5 irrigant flow rates x 2 pressure scenarios; N = 16).

For statistical analysis of the NaOCl extrusion rates, the data were transformed to satisfy the normality and homoscedasticity assumptions prior to analysis with two-factor repeated measures analysis of variance. The latter was used to examine the effects of “irrigant flow rate” and “presence/absence of opposing sinusoidal pressure”, and the interaction of these two factors on NaOCl extrusion rate. Post-hoc pairwise comparisons were conducted using the Holm-Sidak method. Correlation between NaOCl flow rates and extrusion rates for the experimental and the control groups were analysed using Pearson product-moment analysis. For all analyses, statistical significance was set at $\alpha = 0.05$.

3. Results

For the experimental group with opposing sinusoidal pressure, NaOCl extrusion rates corresponding to irrigant flow rates of 15.6, 8.0, 4.0, 3.4 and 3 mL/min were 11.30 ± 0.17, 4.72 ± 0.11, 1.60 ± 0.01, 1.11 ± 0.03 and 0.00 ± 0.00 mL/min, respectively. For the control group without opposing pressure, NaOCl extrusion rates corresponding to irrigant flow rates of 15.6, 8.0, 4.0, 34 and 3 mL/min were 11.78 ± 0.14, 5.37 ± 0.07, 2.31 ± 0.06, 2.28 ± 0.02 and 1.80 ± 0.08 mL/min, respectively (Fig. 3A).

Significance differences were identified for “irrigant flow rate” ($p < 0.001$) and “presence/absence of opposing sinusoidal pressure” ($p < 0.001$), as well as the interaction between the two factors ($p < 0.001$). For the experimental group, NaOCl extrusion rates were in the order 15.6 > 8.0 > 4.0 > 3.4 > 3 mL/min ($p < 0.05$ for all pairwise comparisons). For the control group, NaOCl extrusion rates were in the order 15.6 > 8.0 > 4.0 = 3.4 ($p > 0.05$) > 3 mL/min. For all irrigant flow rates, NaOCl extrusion rate in the presence of opposing sinusoidal pressure was significantly lower than that recorded in the absence of opposing pressure ($p < 0.05$ for all pairwise comparisons).

Second order polynomial relationships existed between NaOCl flow rates and extrusion rates in both the experimental and control groups (Fig. 3B). The Pearson correlation coefficient for the experimental group was 0.998; there was a highly-significant positive correlation between NaOCl flow rates and extrusion rates ($p < 0.0005$). The Pearson correlation coefficient for the control group was 0.999; there

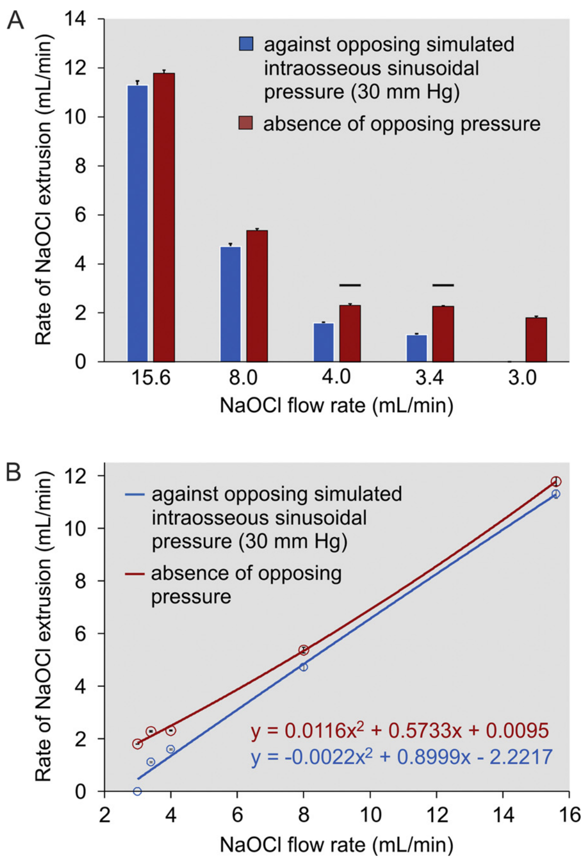

Fig. 3. A. Bar chart representing the rate of NaOCl extrusion (in mL/min) from the apical foramen when NaOCl was delivered from a 30-gauge side-vented needle inserted to 1 mm coronal to the apical seat in a size 30, 0.04 taper faux root canal. Values are means ± standard deviations. For the factor "irrigant flow rate", subgroups indicated by a black bar are not significantly different ($p > 0.05$). For the factor "presence/absence of opposing sinusoidal pressure", NaOCl extrusion rates are all significantly different ($p < 0.05$) between the blue and red columns of each irrigant flow rate. **B**. Second order polynomial regression of NaOCl extrusion rates *vs* irrigant flow rates in the experimental and control groups (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

was a highly-significant positive correlation between NaOCl flow rates and extrusion rates ($p < 0.0001$).

4. Discussion

Although periradicular extravasation of NaOCl may not necessarily result in a NaOCl accident involving facial ecchymosis [10], it is important to prevent this from occurring to minimise operative/post-operative pain and potential delayed healing [32], or symptoms that arise from injecting NaOCl into the maxillary sinus [33]. In the present study, the experimental group simulated the scenario encountered by the majority of teeth in which root apices embedded in medullary bone are opposed by intraosseous sinusoidal pressure. The control group simulated a scenario wherein there is minimal resistance to flow, such as when a root tip is located in the maxillary sinus; root tips projecting into the sinus may be covered only by a thin Schneiderian membrane [34].

Because of the positive correlation between NaOCl delivery and extrusion rates in both the experimental and control groups, the first null hypothesis has to be rejected. Prevention of NaOCl extrusion was only possible when NaOCl was delivered at 3.0 mL/min in the experimental group, whereas NaOCl extrusion was detected at all irrigant flow rates in the control group. It has been postulated that delivery of NaOCl via non-binding, positive-pressure irrigation devices at flow rates faster than 3.4 mL/min has the potential to create a pressure gradient higher than that of the intraosseous space [10]. Existence of a irrigant flow rate threshold in the aforementioned postulation was supported by the results of the experimental group. Because none of the flow rates examined in the control group prevented NaOCl extrusion, one has to exercise caution when irrigant is delivered to maxillary molars with root tips inside the maxillary sinus; a negative-pressure irrigant delivery system appears to be a more rational alternative.

The extrusion rate of NaOCl in the absence of opposing pressure were consistently higher than those in the pressure of opposing sinusoidal pressure, irrespective of the irrigant delivery rate. Hence, the second null hypothesis has to be rejected. This finding implies that there is a tendency for NaOCl extrusion to be over-estimated in studies that did not consider the physiologic contribution of intraosseous venous resistance to periradicular irrigant extrusion [19–28].

Prior to the thesis of NaOCl infusion into intraosseous sinusoids [10], NaOCl extrusion has been envisioned as infusion of the irrigant into the periradicular capillary bed. Park et al. considered the possibility of NaOCl being forced into capillary beds approximating the apical foramen under high apically-directed fluid pressures [35]. The investigators cited capillary pressures ranging from 30 to 40 mm Hg at the arterial end and 10–15 mm Hg at the venous termination. They reported apically-directed pressures exceeding 40 mm Hg in some delivery scenarios, and opined that the periapical and pulp capillaries at the venous end are possible entry sites of NaOCl into the tissues. This scenario is unlikely to happen because unlike suicidal attempts when NaOCl is directly injected into intact vein, periapical capillaries would immediately collapse once they are severed by root canal instruments.

In conclusion, results from the present study supports the biophysics of infusing intraosseous sinusoids with irrigants using a positive pressure delivery device with unsafe delivery rates. The clinical implication of these results is that it is virtually possible to prevent NaOCl extrusion beyond a patent root apex from a side-vented needle inserted to 1 mm short of the working length, when the irrigant is unopposed by fluid resistance derived from the intraosseous venous component.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jdent.2018.08.001.

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