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Syringe Pressure in Root Canal Irrigation: Physics, Clinical Implications, and Risk of Apical Extrusion

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ABSTRACT

After cleaning and shaping during endodontic therapy the root canal space can be disinfected with any number of disinfectants. Sodium hypochlorite is very effective for this. Intracanal lavage via syringe and needle may be done but there is a risk for extrusion of the solution through the tooth apical foramen into the medullary bone. This work studies the canal as a closed system such as when the needle is wedged against the canal walls that prevents solution escape to the coronal. The clinician should appropriately control the pressure placed on the syringe barrel to prevent this extrusion. This article reviews physics, fluid dynamics and factors that may influence an aqueous irrigant to be thrust into the bone. Understanding these factors can prevent perioperative mishaps and tissue damage such as to neural structures. Factors such as syringe diameter, needle lumen, depth of insertion, and flow rate contribute to this occurrence. Experimental and mathematical models were created to investigate this issue. These models were used to quantify a range of forces that would cause breaching of a tooth foramen when using a syringe and needle to deliver the solution. Hand pressure on a syringe is enough to extrude an aqueous solution through an endodontically instrumented tooth apical foramen. There are available side exit needles and other products and techniques that may minimize any apical extrusion.

1. INTRODUCTION

Irrigation for disinfection is an essential step during root canal therapy. This step removes debris,

dissolves organic tissue, and reduces the microbial load in the root canal space. Sodium hypochlorite (NaOCl), household bleach, is the most commonly used irrigant due to its excellent tissue-dissolving and antimicrobial properties [1] [**Figure 1**]. Nonetheless, its cytotoxicity can cause significant tissue damage if it is extruded beyond the root apex into the periapical tissues and the medullary bone [2]. The method of irrigant delivery, particularly the manual pressure generated by syringe irrigation, may be a key factor in this risk [3]. The NaOCl solution is meant to remain confined within the tooth canal space, but it may be possible for the solution to be forced through the apical foramen into the surrounding bone [3]. This can lead to serious complications, including neurological issues, tissue necrosis, and upper airway obstruction [2, 3].

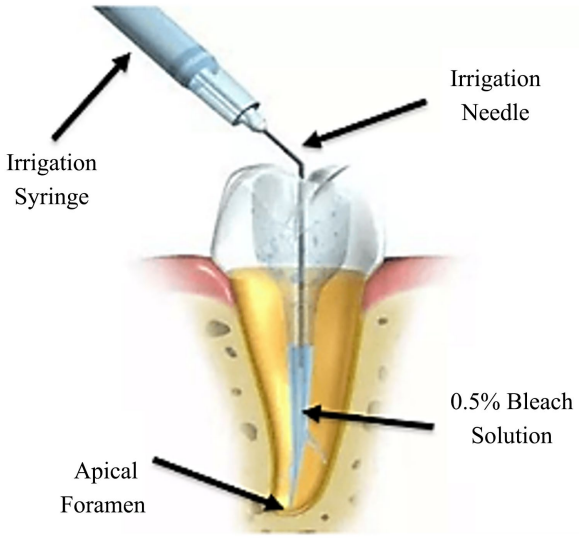

Figure 1. Cartoon of syringe needle lavaing canal space.

Previous in vitro work has demonstrated that increased manual pressure on the syringe barrel can cause extrusion through an orifice even with side vented canulas [4]. Manual forces exceeding 10 Newtons (N) for a 25 G cannula and 40 N for the 30 G cannula had extrusion though the apical orifice [4].

This work discusses the physics underlying syringe pressure, how this pressure interacts with root canal anatomy, and the risk of apical extrusion into periapical tissues. Hand pressure on a syringe is enough to extrude an aqueous solution through an endodontically instrumented tooth apical foramen. The testing design herein may not actually replicate a clinical situation but the aim of this work is to add to the dearth of research on this topic.

2. MATERIALS AND METHODS

Since a bleach solution usually used in clinical practice is extremely diluted, it was considered to be equivalent to plain water in the syringe. Additionally, plain water was used for testing to prevent any injuries to the testing personnel.

The experimental model involved a testing rig designed to enable a repeatable procedure with minimal variability. The rig consisted of a weight loader, syringe holder, force sensor, and data acquisition (DAQ) system. The syringe holder stabilized a 3 mL Luer lock syringe fitted with a 27-gauge beveled needle that was flattened on the end and placed into a root-canal-prepared tooth sample. The needle was cemented with dental resin cement at the mid shaft. The outside of the needle was roughened with a green stone to increase cement purchase to ensure a good seal [**Figure 2**]. Known weights were applied to the syringe plunger in 0.5 kg increments to determine whether the water breached the tooth's apical foramen, and if so, the applied force at which this occurred.

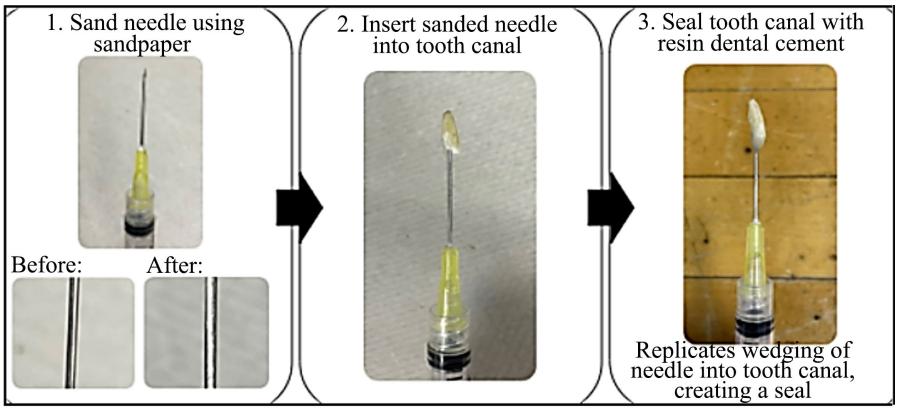

Figure 2. Needle shaft was roughened to improve cement retention and seal then inserted into canal space.

Our mathematical model evaluated the syringe, needle, and tooth assembly as a fluid dynamic system. The fluid velocity and pressure at the tooth's apical foramen were calculated for each applied force to assess whether the water would breach the apical foramen in a living patient. After measuring the area of each tooth sample's apical foramen using a confocal laser microscope, with values ranging from 1057.825 μm^2 to 33538.239 μm^2, the force at which the foramen breached was correlated with the foramen's cross-sectional area [Figure 3]. Both experimental and mathematical results show that there is potential for the water to breach the apical foramen during the disinfection stage of a root canal procedure.

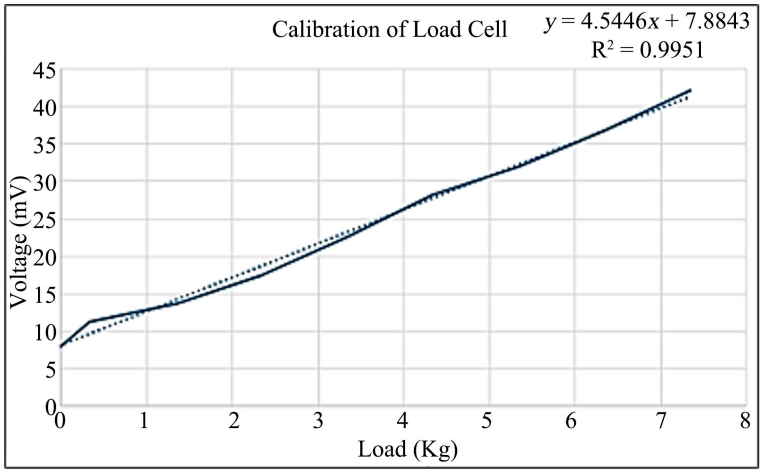

Figure 3. Calibration of load cell.

In this study, there were fourteen teeth previously extracted at a general dental practice in Connecticut, USA, that were cleaned and prepared for testing, all of which are of different sizes, tooth types, and root canal sizes. There were not enough teeth available to use only one uniform type of tooth for the trials. The canal spaces were filed and shaped using K files just to but not beyond each foramen. The coronal of each root canal space was expanded with #3 peezo drills to accept a 27-gauge testing needle. Testing involved fabrication of a rig that would accept a 3 mL syringe filled with water. Weights up to 8 kg were then applied. Each foramen was observed for extrusion of water for 30 seconds to see if the tooth apical foramen was breached. There was a large variance of foramen sizes, canal depth and diameter among the fourteen samples. The difficulty in classifying each tooth must be considered when looking at the final data collected, and the conclusions drawn from the tests.

The final deliverable was to identify a range of forces applied to a syringe and needle assembly, filled with water, that would cause the apical foramen to be breached when the needle is wedged into the canal during injection. To determine this range, three key factors required evaluation: the cross-sectional area of each tooth's sample apical foramen, the range of applied forces, and the pressure at the tooths apical foramen. The cross-sectional area was precisely measured at the micrometer level to characterize each tooth sample for comparison. A range of forces that can realistically be manually applied to a syringe and needle assembly containing water with a needle tip cemented into the root canal space was determined and used for testing. The pressure at the apical foramen was mathematically calculated, for each foramen area and at each applied force, to predict if the foramen would breach in an endodontic patient.

Codes and Standards

The TE Connectivity FX292X, a standard button load cell rated for up to 50 lbs. of force, is used to measure the force applied to the syringe, needle, and tooth system. According to the manufacturers' specifications in the datasheet (Appendix A), the supply voltage for the load cell must not exceed 6 volts for an analog millivolt output, the device should be stored in at temperatures between −40˚C to 85˚C, and the applied compressive load should not exceed 2.5 times its rated capacity to avoid damaging the sensor. The USB-1208FS, our data acquisition unit, from Measurement Computing Co. also has similar specifications (linked in Appendix A), including an operational temperature range of 0˚C to 70˚C and has a maximum analog voltage input of 10 volts. While these may seem like basic specifications, but they are critical to ensure safe operation, prevent equipment damage, and maintain accurate performance (ASME. (2018). *Y14.5—Dimensioning and Tolerancing-ASME*. Asme.org. https://www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing)

Utilizing a load cell for force measurements requires adherence to manufacturer guidelines and industry standards to ensure accurate and reliable data. (ISO—7500-1 S *Metallic materials—Calibration and verification of static uniaxial testing machines*), outlines the procedure of calibration of load cells [**Figure 4**]. For the TE Connectivity FX292X, we followed the calibration outlined in section 6.4.5 *Application of discrete forces*, which involves applying five discrete forces across the *l*oad cell's operating range, starting at 20% of its maximum rating, and increasing up to 100%. Additionally, 6.4.2 *Temperature compensation* specifies that recalibration is necessary if there is a temperature change in the environment exceeding 2˚C.

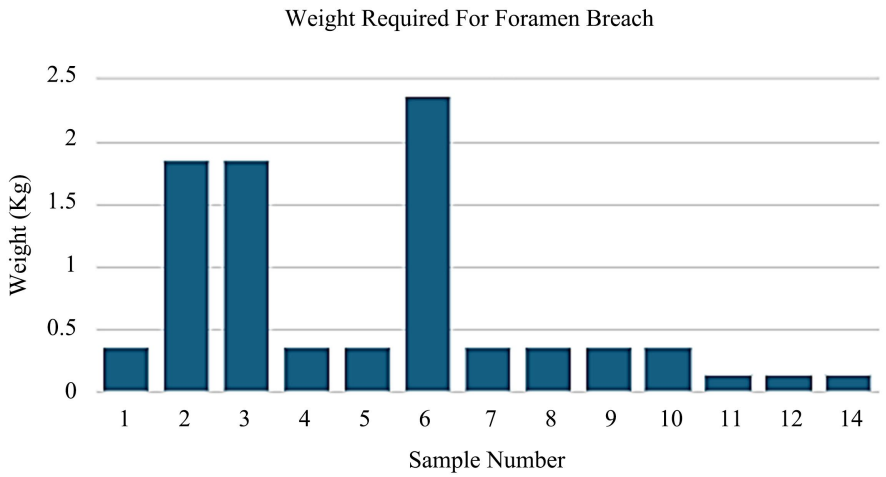

Figure 4. Weight required for the solution to breach the tooth apical foramen.

In alignment with these standards, we recalibrated the load cell each day of testing to ensure this critical step is followed so that an accurate force reading was obtained.

In this project, SolidWorks has been used for various tasks including the design of 3D printed parts and machining for use in our test rig. The ASME Y14.5—*Dimensioning and Tolerancing Standard* dictates

how to represent and exchange information on technical drawings. It covers things from general toleranc-ing, symbols, datum reference frames, and dimensioning. SolidWorks, as an industry standard CAD pro-gram, is designed to adhere to these standards for industry practice to ensure customers, such as us, can create detailed part drawings with accurate dimensions, tolerances, and annotations. Adherence to this standard promotes consistency and readability across technical documents and compatibility between dif-ferent CAD platforms and engineering teams.

Testing Rig

To conduct the testing, we developed a custom testing rig based on a standard 3/8" rod ring stand, which we modified by incorporating 3-D printed and machined components, a load cell, and a Data Acqui-sition system. The complete setup used for all data collection is shown in **Figure 2(a)**. **Figure 2(b)** and **Figure 2(c)** provide closer views of the bottom and top sections of the setup respectively.

There are three gray components attached to the stand, referred to as rig stabilizers which secure the loading rod to the base, allowing for sliding of the loading rod during experimentation. The bottom stabilizer also serves as a syringe holder, featuring a custom-designed cutout that matches the shape of the syringe to ensure a snug fit and minimize movement during testing [**Figure 2**]. Mounted on the top of the syringe plunger is a black circular piece designed to hold our load cell securely in place. The load cell, shown in **Figure 2(b)**, connects via wires to the data acquisition system (USB-FS1208). The loading rod, which passes through the stabilizers, includes a weight loader, the large red component, where calibrated 0.5 kg weights are added during testing. At the bottom of the rod, a plastic footing on a swivel ensures the applied force remains normal to the load cell. The final component of the test rig is the set of aluminum plates, visible on both sides of the stabilizers. These plates were designed and machined by the team to fasten directly into the stabilizers, preventing rotation during testing. Isometric views of all custom-designed, along with the de-tailed drawing for the machined plates, are provided in Appendix.

Sample Preparation

The second key component of the final setup is the tooth samples being tested. Each tooth sample had an access hole drilled into the occlusal fossa to simulate a root canal procedure. Each needle was secured into the canal space using dental resin cement. To improve adhesion, the outer surface of the provided needles was roughened with a green stone. The needle was then inserted into the canal, and resin cement was applied around the needle shaft to completely seal the connection between the needle and access open-ing. This sealing process was a critical step to ensure there was no fluid leaking from this connection. For some samples, there were signs of leakage at the connection during initial testing. In this case, the tooth was resealed by applying additional cement to the connection until a complete seal was demonstrated. **Figure 5** illustrates this process that was followed for all fourteen samples tested [**Figure 6**].

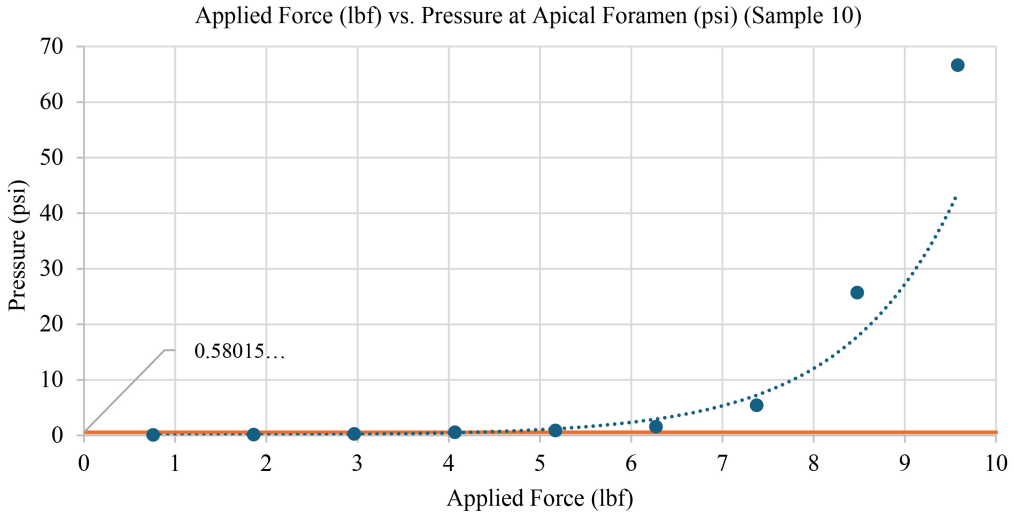

Figure 5. Graph depicting the applied force vs pressure at the tooth apical foramen.

Mass Applied (known) (kg)	Force Applied (known) (N)	Syringe Volume (mL)	Syringe Volume (m^3)	Time (s)	Time (min)	Q (m^3/s)	Syringe Plunger Area (m^2)	Apical Foramen Area (m^2)	Fluid Velocity 2 (m/s)	Water Density (kg/m^3)	Pressure 1 (psi)	Pressure 2 (psi)	Change in Pressure (psi)
0.3445	3.379545	0.5	5.00E-07	29.7	0.495	1.68E-08	5.88E-05	3.35E-08	5.02E-01	998	8.34E+01	8.30E+01	3.65E-02
0.8445	8.284545	0.5	5.00E-07	16.85	0.280833	2.97E-08	5.88E-05	3.35E-08	8.85E-01	998	2.04E+01	2.03E+01	1.13E-01
1.3445	13.18955	1	1.00E-06	24.85	0.414167	4.02E-08	5.88E-05	3.35E-08	1.20E+00	998	3.26E+01	3.23E+01	2.08E-01
1.8445	18.09455	2	2.00E-06	31.7	0.528333	6.31E-08	5.88E-05	3.35E-08	1.88E+00	998	4.47E+01	4.41E+01	5.12E-01
2.3445	22.99955	2	2.00E-06	24.65	0.410833	8.11E-08	5.88E-05	3.35E-08	2.42E+00	998	5.68E+01	5.59E+01	8.47E-01
2.8445	27.90455	2	2.00E-06	18.34	0.305667	1.09E-07	5.88E-05	3.35E-08	3.25E+00	998	6.89E+01	6.73E+01	1.53E+00
3.3445	32.80955	2	2.00E-06	9.79	0.163167	2.04E-07	5.88E-05	3.35E-08	6.09E+00	998	8.10E+01	7.56E+01	5.37E+00
3.8445	37.71455	2	2.00E-06	4.48	0.074667	4.46E-07	5.88E-05	3.35E-08	1.33E+01	998	9.31E+01	6.74E+01	2.56E+01
4.3445	42.61955	2	2.00E-06	2.78	0.046333	7.19E-07	5.88E-05	3.35E-08	2.15E+01	998	1.05E+02	3.86E+01	6.66E+01

Figure 6. Graph relating the known applied mass the applied force to the syringe, the syringe volume, the time frame the force was applied, the tooth apical foramen area, the fluid velocity, and change in pressure.

Data Acquisition System—USB-1208FS

A data acquisition system is necessary for reading and recording the output of the load cell. A USB-1208FS DAQ made by Measurement Computing was provided by the University of Connecticut, School of Engineering [Appendix]. This device reads the analog output from the load cell.

In addition to the physical DAQ hardware, two software tools were provided by the manufacturer, DAQami and InstaCal. InstaCal allowed us to configure and test the DAQ system by assessing analog and digital connections and generating internal signals, such as a continuous sine wave to verify functionality. DAQami records the data collected from the load cell and exports it to Excel files. The outputs include two columns of data, time and voltage. These files can be analyzed in Microsoft Excel or imported to other data analysis tools for further processing.

Testing

Confocal Laser Microscope Measurements

To characterize each of the samples tested, the area of the apical foramen of each tooth sample was measured. A confocal laser microscope was used to identify the foramen and measure its cross-sectional area. In Table 1, the area measurements of the 14 tooth samples range from 1057.825 μm to 33538.239 μm.

Table 1. Apical foramen cross section.

Sample	Apical Foramen Cross-Sectional Area (μm)
1	25714.728
2	1057.852
3	1255.473
4	1427.096
5	20100.185
6	2098.161
7	5855.068
8	1783.163
9	5754.250
10	33538.239

Continued

11	19817.445
12	11107.128
13	33009.419
14	8889.338

Load Cell Calibration Procedure

The load cell calibration process was done by mounting the load cell into the test rig, securely placed within its holder to prevent any movement or misalignment during testing. The data acquisition system is then connected and confirmed to be functioning properly. Prior to applying any load, the system is zeroed with no weight on the load cell to establish a baseline reading. Certified calibration weights are applied incrementally, beginning at zero and increasing up to 150% of the maximum load expected during experimentation, using five calibration points throughout this range. (*Metallic materials—Calibration and verification of static uniaxial testing machines*. (n.d.). https://cdn.standards.iteh.ai/samples/72572/aae48e1d33a544a198577be7289fc1d7/ISO-7500-1-2018.pdf)

At each point, both the applied weight and corresponding output voltage from the load cell were recorded. After all points were recorded, the data was used to generate a calibration curve (**Figure 3**). The applied force in kilograms is plotted versus the output voltage in millivolts, and a linear fit is applied. In this example, the linear regression yielded a 0.995 value for R^2, indicating an excellent fit between applied force and load cell output. With an acceptable fit confirmed, the equation of the line was used to calculate applied forces during testing, completing the calibration process for the load cell.

Testing Procedure

The testing procedure was initiated by calibrating the load cell using the method described above. An empty syringe was secured into the syringe holder, then filled with 3 mL of water. The load cell and its holder are then placed on top of the syringe plunger, which was followed by attaching a needle containing a prepared tooth sample onto the water filled syringe. Once this setup was completed, load cell recording was begun, and the weight loader rod was released to apply the initial load, 0.3445 Kg, and data was taken for 30 seconds. During this time, observations were recorded if there was any water leakage from the tooth apex or the needle seal. A breach of the apical foramen in the form of bubbling or a stream of water from the foramen was a visual indication. After the first measurement, data from that trial was exported to an Excel file for later analysis. A 0.5 kg weight was then added to the weight loader and the process was repeated. Starting from releasing the rod and continuing with observation and data recording, until the foramen of the tooth was breached. If the foramen remained unbreached after adding the maximum calibrated weight of 8 kg, additional force was manually applied, and all relevant observations and load cell data were recorded [**Figure 4**].

Human Manual Compression

The testing team conducted individual testing to determine each person's personal manual force capability. Each group member took a syringe, with the plunger barrel in the bottom position, then at rest, then in-hand with the load cell in its holder on the top of the plunger and then pushed with maximal effort. **Table 2** displays these results.

Table 2. Maximum manual force generated by each member of the team.

Manual Applied Force (kg)	Team Member 1	Team Member 2	Team Member 3	Average
Minimum	2.09	1.45	0.68	1.41
Moderate	3.22	2.90	3.27	3.13
Maximum	4.13	3.95	4.45	4.17

These forces were done by a small group but demonstrate that these forces magnitudes were well about the critical apical foraminal breach [Table 2].

3. RESULTS

Testing Results

Fourteen tooth root samples were tested, all exhibited breaching of the apical foramen at forces ranging from 0.124 kg to 2.3445 kg. Figure 4 displays each sample alongside the weight applied at which the apical foramen of the tooth breached [Figure 4]. A breach was considered any visible fluid, dripping, bubbling, or a continuous stream emanating from the tooth apical foramen.

Mathematical Approach

Mathematical modeling was used to calculate the pressure at the tooth's apical foramen. This value is important in that it serves as a benchmark for comparison against intraosseous space blood pressure. To determine the pressure at the foramen, the syringe, needle, and tooth were treated as a single fluid dynamic system.

Using the linear momentum equation (for a control volume), Equation (1), is a formula representative of the dynamics within the syringe, needle, and tooth assembly was formulated, and then simplified to Equation (2).

$$\sum F = \frac{\mathrm{d}}{\mathrm{d}t}\int_{CV} V\rho \mathrm{d}V + \int_{CS} V\rho V \mathrm{d}A \tag{1}$$

$$\sum F = \frac{\mathrm{d}mV_{CV}}{\mathrm{d}t} + \frac{\mathrm{d}m(t)}{\mathrm{d}t} \tag{2}$$

The first term in Equation (2), $\frac{\mathrm{d}mV_{CV}}{\mathrm{d}t}$, may be negligible if there is an assumption that the fluid velocity at the apical foramen, V_2, is significantly greater than the fluid velocity at the interface between the syringe plunger and water surface, V_1. This enables simplification to Equation (3). Solving for P_2, the pressure at the tooth apical foramen, the equation is further simplified to Equation (4).

$$P_1A_2 - P_2A_2 = \rho QV_2 \tag{3}$$

$$P_2 = P_1 - \frac{\rho Q^2}{A_2^2} \tag{4}$$

Mathematical Results

In Figure 5, the applied force versus the pressure at the tooth's apical foramen for Sample 10 is shown [Figure 5]. There is a clear exponential relationship between the two variables. The orange horizontal line at a pressure of 0.58 psi represents the threshold we are measuring against—this value corresponds to the intraosseous space blood pressure, which is the physiological pressure present at the tooth's apical foramen, as established by multiple publications. If the measured pressure exceeds this threshold, it indicates that the fluid would likely breach the apical foramen if this were occurring in an actual patient. At an applied force of 5.17 lbf and greater, the pressure exceeds the intraosseous space blood pressure, indicating that the apical foramen would breach at this point.

4. DISCUSSION

Fluid Dynamics of Syringe Irrigation and Bernoulli's Principle and Flow Rate

In syringe irrigation, fluid is driven by the force exerted on the plunger causing water to be expressed through the needle. According to Bernoulli's principle and Hagen-Poiseuille's law, flow rate [Q] through a cylindrical canal is affected by the pressure differential, the viscosity of the fluid, and the radius and length of the canal or needle:

$$Q = \frac{\pi r^4 \Delta P}{8\eta L}$$

where:

- r = radius of the needle or canal,
- ΔP = pressure gradient,
- η = dynamic viscosity,
- L = length of the canal/needle.

A smaller needle bore increases resistance and reduces flow unless compensated by increased pressure, which can increase the risk of apical extrusion.

Syringe Force and Generated Pressure

For syringe irrigation, a clinician may opt for 5 - 10 mL syringes with 27 to 30-gauge needles. Studies have shown that manual irrigation pressure can exceed 3.75 N [Newtons] [5-9]. The pressure generated depends on syringe diameter: smaller syringes (e.g., 3 mL) generate higher pressure for the same applied force compared to larger syringes (e.g., 10 mL). A pressure over 100 kPa can be generated easily with forceful irrigation [5-9] [**Figure 6**].

Apical Extrusion

There is little published information as to the extrusion of liquid irrigants through the tooth apical foramen. These are usually case reports of operative accidents. There is a dearth of evidence for the factors that allow the extrusion. In vitro studies have a major limitation in that there are no apical tissues to simulate clinical actualities. There are variable protocols that prevent a uniform view for evaluation.

The position of the delivery needle end in the canal space influences the risk for extrusion. This is when the needle reaches a binding level in the canal space where the needle cannot be advanced any further. There will be a variety of positions for this in clinical situations. The position may be estimated with the formula:

$$L = \frac{D_N - A}{T}$$

where L = distance from the apex, D = needle external diameter, A = prepared apical canal space diameter, T = taper of the prepared canal space.

All endodontic glide path techniques can cause apical extrusion [3]. Where there is inflammation or necrotic apical tissue there may be a lack of an effective medullary barrier. The barrier from non-pathogenic periapical tissues may resist solution extrusion [5, 7].

Studies in cadaver models show that extrusion occurs at apical pressures as low as 7 - 15 psi (48 - 103 kPa) depending on apical diameter and presence of periapical lesions [7].

Conditions Leading to Extrusion

Samples #2, 3 and 6 required more than 1.7 kg to express the water out of the apex [**Table 1** and **Table 2**]. All the other teeth with larger foramina did not require larger weight to extrude the water. Thus, there are other factors that play a role in producing an extrusion of water. The roots were not sectioned and examined for differences that may affect the outcomes. Nonetheless, it appears that the apical foramen may not be the most important factor in an array of parameters in allowing the water to extrude. An apical tunnel or the presence of apical irregularities or remnant debris may affect extrusion.

Apical extrusion may be more likely under the following conditions:

- Needle binding in the canal without allowing backflow leakage.
- Excessive plunger force during irrigation.
- Use of large-diameter syringes with small-gauge needles.
- Open or widened apical foramina.

Clinical Implications

Sodium Hypochlorite Accidents

Iatrogenic NaOCl extrusion can result in acute pain, edema, ecchymosis, necrosis of the periapical tissues, loss of sensation, and extend into fascial planes and medullary bone [4]. These complications can be

related to apical medullary pressure and tissue permeability [4, 7, 10].

Apical Peri-root Tissue

The presence of pathology may affect extrusion in that cohesive cells may resist any apical extrusion [7, 10].

Apical extrusion of solid material or liquid may be vastly different and occur under a variety of conditions [11, 12].

Medullary Bone Entry

If NaOCl breaches the apical constriction, it can pass through nutrient canals into cancellous (medullary) bone or out into facial tissue via foramina. Bone marrow sinusoids and venous structures may allow rapid dissemination of the solution, causing localized osteonecrosis and systemic symptoms [1, 4].

Side vented irrigation needles may not induce significant extrusion [9]. Nonetheless, the manual force exerted on the syringe barrel is well beyond the magnitude of force required to cause an extrusion if the intracanal pressure. This may be true if intracanal pressure exerted exceeds the apical critical breach especially if there is any blockage near the coronal canal space.

Suggestions for Syringe Irrigation of Endodontic Canal spaces

- Use side-vented needles and avoid wedging the needle into the canal space, but the solution may not reach the apical space.
- Keep the needle 2 - 3 mm short of the working length, but this may not lavage the apical canal space.
- Apply minimal finger pressure during irrigation.
- Use lower-pressure delivery systems (negative pressure or activated irrigation devices).
- Avoid using syringes smaller than 5 mL to reduce peak pressures.
- Instead of syringe lavage, use paper points measured to the working length and soaked in bleach to lavage the internal walls of the canal space down to the apical canal space.

Clinical Implications

Small amounts of irrigant extrusion may occur during routine root canal instrumentation, but serious extrusion accidents are typically associated with immediate acute symptoms following irrigation. Therefore, this work focuses specifically on factors influencing irrigant extrusion during canal space irrigation.

Clinical evidence on this topic is limited to case reports. Case reports are a low-level of evidence and may not present predisposing factors. It appears that extrusion accidents are a result of a combination of technique and anatomical factors [10-12].

Extrusion can occur in vital and nonvital teeth. In vital teeth, accidents were associated with needle point wedging, over-instrumentation, and canal space perforations. In nonvital teeth, periapical lesions, bone defects, sinus communications. Reduced bone thickness around apices can increase the risk for an extrusion [11-13].

Open-ended needles mounted on syringes seem to be commonly found in extrusion accidents. It may not be possible to quantify the volume of an extruded liquid and the relationship between irrigant volume, concentration, and tissue damage uncertain. Although greater volume likely increases tissue injury severity [11-13].

Needle delivery of intracanal solutions may be subject to an apical vapor lock which may prevent apical contact with the solution [11-13].

In vitro research is focused on irrigation systems and not anatomy-related risk factors such as perforations, periapical lesions, or needle wedging. Irrigation methods should balance cleaning efficacy with patient safety, and an extrusion risk should be considered when comparing an irrigation technique [11-13].

Apical extrusions are generally "classified" as "accidents". Technique errors may result in an accidental extrusion. Wedging the needle tip against the root canal walls would likely cause an apical closed space. This work, herein, has shown that only a small force on the syringe barrel is necessary to cause an aqueous solution to breach the apical foramen into the medullary bone. This apparently may overcome an apical vapor lock of the solution.

Limitations of This Work

Each apical foramen can be very small so that even using a laser microscope it can be difficult to ensure

the foramen is being measured and investigated properly. While the laser microscope is very accurate at characterizing the size and depth of each foramen, it is very sensitive to the angle at which the tooth is placed. If the foramen, which is not always at the apical tip, is not perfectly coaxial with the lens of the microscope, there is room for error in the measurement of that apical foramen. While this has not been deemed a major issue, it may need to be considered in a large range of cross-sectional areas of the apical foramina measurements.

A vapor lock, an interruption of the liquid flow due to vaporization of the liquid, can occur with syringe delivered medicaments [11-13]. None was detected during this work. The force on the syringe may overcome any vapor lock.

The testing was done in the form of a closed system, which may not replicate the clinical situation. A clinician may, in error, wedge the needle against the walls of the root canal and unintentionally create a closed space. This would not allow any escape of any pressurized irrigant except via the foramen. The clinician may push the needle until it stops. This would place the tip not in the apical canal and would wedge the point against the canal walls and potentially create a water-tight seal thus creating a closed system except for the apical foramen. This creates a situation similar as to what this work is testing.

These tests did not measure the intracanal pressure due to the complexity and associated costs. While the testing design may not truly and accurately replicate an actual clinical situation, wedging of the needle against the canal walls can occur creating a closed system. The aim of this work is to add a bit to the dearth of research on this topic. We cannot not delve into a complete clinical examination of intracanal irrigation in the scope of this work.

5. CONCLUSIONS

The risk of irrigant extrusion into periapical tissues and medullary bone is a function of the pressure generated during syringe irrigation and the resistance offered by apical tissues. Understanding the physics behind irrigation pressure, along with proper clinical technique, is important for safe and effective endodontic lavage. Maximal hand pressure far exceeds the pressure required to cause an extrusion.

This investigation has demonstrated that when a needle is wedged and cemented into a tooth in this specific configuration, fluid is usually forced to exit through the apical foramen, even under relatively low applied forces. The weight required to breach the apical foramen in such scenario's ranges from 0.124 kg to 2.3445 kg, forces that could theoretically be exerted by a hand-held injector syringe during a root canal procedure.

This finding underscores the importance of exercising extreme caution during this phase of the root canal process. To minimize the risk of breaching the apical foramen, it is recommended that:

1) The clinician should ensure the needle is not wedged within the tooth and yet is inserted deeply enough to effectively disinfect the complete canal.

2) The solution should be injected at a very slow and controlled rate. This precaution allows for minimal applied force, reducing the likelihood of accidental extrusion even if the needle becomes temporarily wedged against the sides of the canal space.

3) Use an alternative technique such as paper point lavage.

These measures help maintain procedural safety and prevent complications, ensuring the precision of the root canal treatment. Additionally, it is important to consider factors that are clinically relevant that were not considered in our testing procedure. Some of these factors could include different types of teeth having varying geometries and lumen profiles, and foramen sizes. Additionally, solution strengths may be a variable issue. These factors were not taken into consideration during testing, but in a clinical setting, these could be relevant. Irrigant delivery by syringe may not be optimal.

Apical extrusion during root canal space irrigation involves multiple factors that need consideration. There are significant gaps in the literature on irrigant extrusion during root canal treatment. Future studies need to elucidate specific factors for extrusion prevention so as to appropriately arm the clinician.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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ABBREVIATIONS

Q = Flow Rate
A = Area
υ = Velocity
P = Pressure
ρ = Density
F = Force
g = Gravitational Acceleration
V = Volume
CS = Control Surface
CV = Control Volume

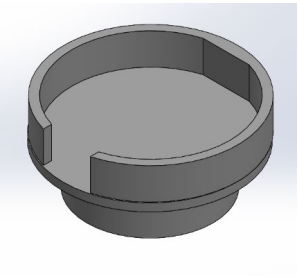
APPENDIX A

TE Connectivity's (TE) FX29 Load Cell Datasheet:
https://www.te.com/commerce/DocumentDelivery/DDEController?Action=srchrtrv&DocNm=FX29&DocType=Data%20Sheet&DocLang=English&DocFormat=pdf&PartCntxt=20009605-06

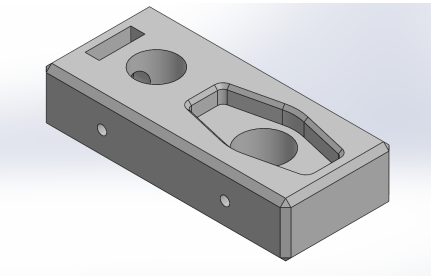
USB-1208FS Datasheet:
https://files.digilent.com/datasheets%2FDS-USB-1208FS-Plus-LS-1408FS-Plus-Series.pdf?cjdata=MXxOfDB8WXww&cjevent=54aafec00b1c11f0838e077a0a82b820&utm_source=cj&utm_medium=referral&utm_campaign=affiliate&utm_content=100357191

Mass Applied (known) (kg)	Force Applied (known) (N)	Syringe Volume (mL)	Syringe Volume (m^3)	Time (s)	Time (min)	Q (m^3/s)	Syringe Plunger Area (m^2)	Apical Foramen Area (m^2)	Fluid Velocity 2 (m/s)	Water Density (kg/m^3)	Pressure 1 (psi)	Pressure 2 (psi)	Change in Pressure (psi)
0.3445	3.379545	0.5	5.00E-07	29.7	0.495	1.68E-08	5.88E-05	3.35E-08	5.02E-01	998	8.34E+01	8.30E+01	3.65E-02
0.8445	8.284545	0.5	5.00E-07	16.85	0.280833	2.97E-08	5.88E-05	3.35E-08	8.85E-01	998	2.04E+01	2.03E+01	1.13E-01
1.3445	13.18955	1	1.00E-06	24.85	0.414167	4.02E-08	5.88E-05	3.35E-08	1.20E+00	998	3.26E+01	3.23E+01	2.08E-01
1.8445	18.09455	2	2.00E-06	31.7	0.528333	6.31E-08	5.88E-05	3.35E-08	1.88E+00	998	4.47E+01	4.41E+01	5.12E-01
2.3445	22.99955	2	2.00E-06	24.65	0.410833	8.11E-08	5.88E-05	3.35E-08	2.42E+00	998	5.68E+01	5.59E+01	8.47E-01
2.8445	27.90455	2	2.00E-06	18.34	0.305667	1.09E-07	5.88E-05	3.35E-08	3.25E+00	998	6.89E+01	6.73E+01	1.53E+00
3.3445	32.80955	2	2.00E-06	9.79	0.163167	2.04E-07	5.88E-05	3.35E-08	6.09E+00	998	8.10E+01	7.56E+01	5.37E+00
3.8445	37.71455	2	2.00E-06	4.48	0.074667	4.46E-07	5.88E-05	3.35E-08	1.33E+01	998	9.31E+01	6.74E+01	2.56E+01
4.3445	42.61955	2	2.00E-06	2.78	0.046333	7.19E-07	5.88E-05	3.35E-08	2.15E+01	998	1.05E+02	3.86E+01	6.66E+01

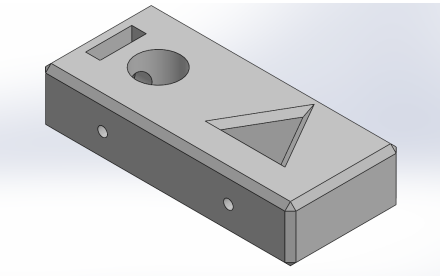
APPENDIX B



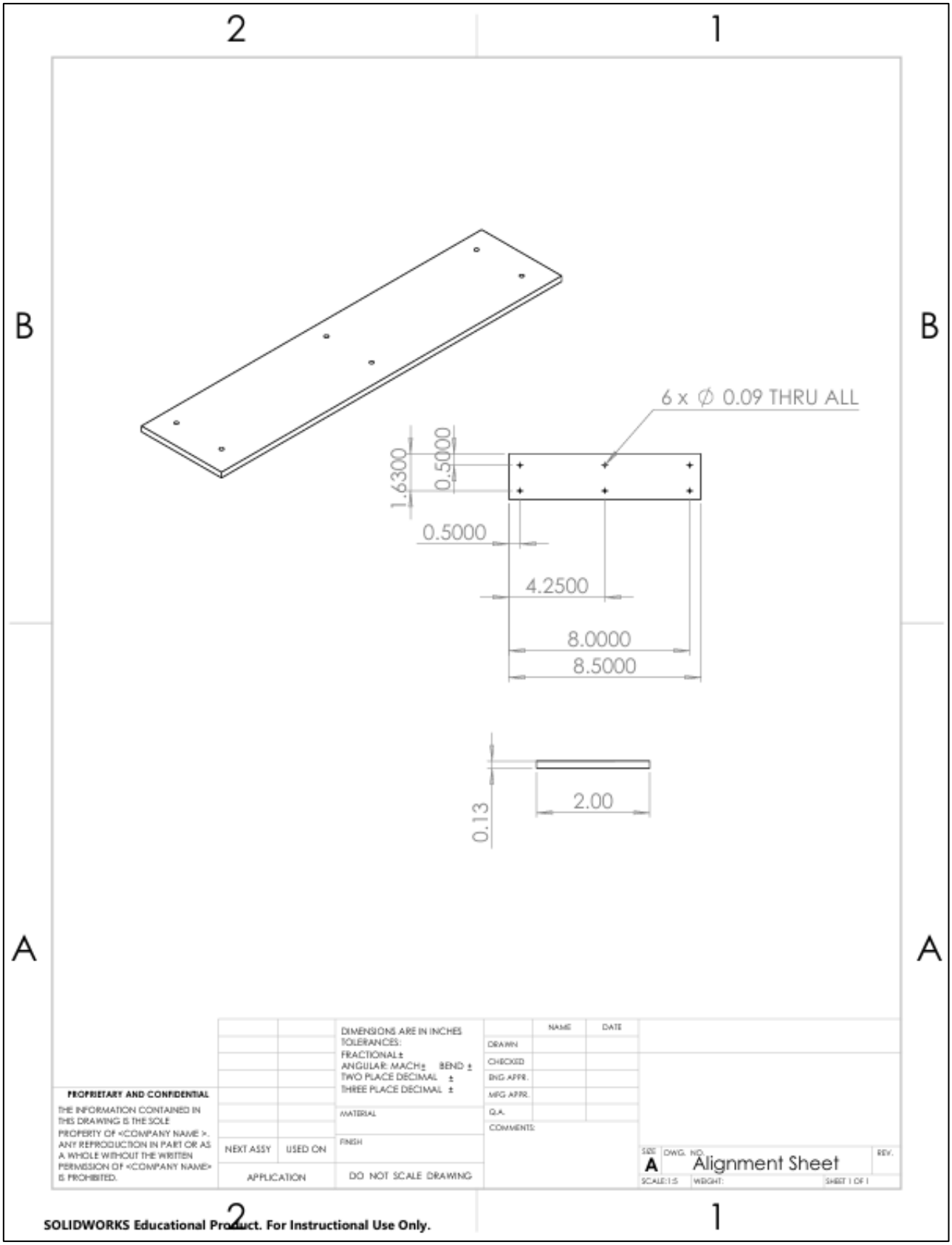
Load Cell Holder



Rig Stabilizer-Syringe Holder



Rig Stabilizer



Alignment Sheet Drawing

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