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Development of a Compact Chairside Ultrasonic Post-Etch Cleansing Unit for Hydrofluoric Acid-Etched Lithium Disilicate: Design and Fabrication

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KEYWORDS

Lithium disilicate; hydrofluoric acid; post-etch cleansing; ultrasonic cleansing; chairside device; device fabrication; adhesive dentistry

ABSTRACT:

Introduction: Reliable adhesive bonding to lithium disilicate depends not only on hydrofluoric acid etching, but also on effective removal of post-etch reaction residues before silanization and resin cementation. Although ultrasonic cleansing has been investigated as a useful adjunct to postetch cleaning, chairside use remains poorly standardized because conventional laboratory ultrasonic baths are not specifically designed for this step.

Objectives: To describe the design and fabrication of a compact chairside ultrasonic post-etch cleansing unit intended to standardize cleansing of hydrofluoric acid-etched lithium disilicate.

Methods A technical development workflow was undertaken beginning with identification of the clinical and laboratory requirements for a dedicated post-etch cleansing device. The unit was conceptualized as a compact single-chamber system that could be used chairside after hydrofluoric acid etching and phosphoric acid cleansing. Computer-aided design was used to develop the main body, lid, and internal perforated specimen cage. The final design incorporated a polycarbonate external housing with a metallic inner cleansing assembly and a removable perforated cage to permit solution access, specimen containment, and easy retrieval. Based on the finalized design drawings, the main body measured approximately 173 × 78 × 83 mm, with an internal cage measuring 151 × 48 × 73 mm. The lid was designed to provide enclosure during cleansing while preserving ease of access and operability. Design priorities included compactness, structural stability, chemical compatibility, chairside handling, and standardization of specimen cleansing.

Results: The final prototype was successfully developed as a compact single-chamber chairside ultrasonic cleansing unit with three principal components: main body, perforated internal cage, and lid assembly. The design permitted organized placement and retrieval of etched specimens, adequate exposure of the specimens to cleansing solution, and a practical chairside footprint. The perforated cage architecture allowed fluid communication during ultrasonic activation while minimizing specimen displacement. The completed prototype was suitable for incorporation into the experimental workflow for post-etch cleansing of lithium disilicate specimens.

Conclusions: A novel compact chairside ultrasonic post-etch cleansing unit was successfully designed and fabricated for standardized cleansing of hydrofluoric acid-etched lithium disilicate. The prototype offers a practical platform for controlled post-etch cleansing and may improve procedural standardization in laboratory investigations and future clinical translation.

1. Introduction

Lithium disilicate glass-ceramic is widely used for indirect esthetic restorations because it combines favorable optical properties with satisfactory mechanical performance. However, the clinical success of lithium disilicate restorations depends not only on the ceramic itself, but also on the quality and consistency of the adhesive bonding protocol used during cementation [1,2]. The resin-ceramic interface is therefore a critical determinant of long-term restorative performance.

For silica-based ceramics, hydrofluoric acid (HF) etching followed by silane application remains the most accepted surface treatment approach. HF selectively dissolves the glassy matrix and creates a microretentive surface, while silane improves chemical interaction between the ceramic substrate and resin cement [2-4]. Previous studies have shown that both the etching protocol and silane treatment can significantly influence bond strength to lithium disilicate [3,4]. At the same time, HF is a hazardous material, and its clinical use demands caution

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because of its well-recognized corrosive and toxic effects [5].

Despite its effectiveness, HF etching is not a residue-free process. Etching can leave fluoridecontaining and other reaction by-products on the ceramic surface, which may obstruct the etched microstructure and interfere with subsequent silanization and resin infiltration if they are not adequately removed [2,6]. For this reason, several post-etch cleansing methods have been investigated, including water rinsing, phosphoric acid application, and ultrasonic cleaning. Belli et al. reported that post-etch cleaning affected resin-ceramic bonding and surface chemistry [6]. Giraldo et al. found that active application of phosphoric acid improved the bond strength of lithium disilicate compared with passive application protocols [7]. Similarly, dos Santos et al. showed that ultrasonic cleaning was effective in removing residual fluorosilicate salts and produced the highest shear bond strength among the tested cleansing methods [8].

More recent work has further supported the importance of this step. Agarwal et al. demonstrated that post-etch cleansing improved the surface microstructure, surface topography, and microshear bond strength of lithium disilicate when compared with HF etching alone, with the best results observed when phosphoric acid cleansing was followed by ultrasonic bath treatment [9]. These findings suggest that post-etch cleansing should not be viewed as an optional adjunct, but rather as an important part of the bonding protocol.

However, although ultrasonic cleansing has shown promise in laboratory studies, the available protocols have generally relied on conventional ultrasonic baths rather than compact devices specifically configured for dedicated chairside use [8,9]. This creates a practical gap between experimental evidence and routine clinical application. In restorative practice, procedural standardization, compact design, ease of handling, specimen containment, and safe chairside operability are all relevant considerations when translating a laboratory cleaning method into a usable device. This gap provides the rationale for developing a purpose-built ultrasonic unit specifically intended for post-etch cleansing of HF-treated lithium disilicate. The aim of the present technical report is therefore to describe the design rationale, component development, and fabrication of a novel chairside ultrasonic post-etch cleansing unit intended to standardize this step before silanization and adhesive cementation.

2. Methods

Study design

This work was designed as a technical development study describing the conceptualization, computer-aided design, material selection, fabrication, assembly, and preliminary functional appraisal of a compact chairside ultrasonic post-etch cleansing unit intended for use with hydrofluoric acid (HF)-etched lithium disilicate. The design brief was derived from published evidence showing that post-etch cleansing, particularly when phosphoric acid cleaning is followed by ultrasonic agitation, improves surface cleanliness and bond-related outcomes of lithium disilicate when compared with HF etching alone [6-9]. In parallel, the workflow was informed by the growing use of digital design and additive manufacturing approaches for dental devices and custom technical components [10-12].

Design objectives and functional requirements

At the outset, the unit was planned to address a specific procedural gap between published laboratory cleansing protocols and practical chairside implementation. The primary design objective was to create a dedicated single-chamber ultrasonic unit that could standardize the cleansing step performed after HF etching and before silanization. Based on the intended use, the device was required to:

(1) provide a compact chairside footprint;

(2) accommodate small ceramic specimens in a stable and retrievable manner;

(3) allow unrestricted entry and circulation of the cleansing medium around the specimen surfaces;

(4) minimize specimen displacement during cleansing;

(5) permit easy operator access for placement and removal of specimens; and

(6) provide a covered configuration during operation. These requirements were defined in response to the known importance of post-etch residue removal and the recognized role of ultrasonics in fluid agitation and debris dislodgement [6-9,13].

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Concept development

Initial concept development involved translating the cleansing sequence into a dedicated device architecture. Earlier multi-component ideas were simplified into a single-chamber configuration to reduce overall bulk, facilitate chairside handling, and minimize procedural complexity. The finalized concept consisted of three principal parts:

1. an outer main body,
2. a removable perforated internal cage, and
3. a lid assembly with hinge support.

The outer body functioned as the structural housing of the unit. The removable internal cage was designed to hold ceramic specimens within the cleansing chamber while allowing the cleansing medium to access all surfaces. The lid was planned to cover the chamber during operation and to support convenient repeated opening and closing without disturbing the position of the cage.

Computer-aided design workflow

All components were developed using a computer-aided design (CAD) workflow before fabrication. Orthographic drawings and isometric renderings were generated for the main body, lid, and internal cage. This digital approach was selected because CAD-based workflows have become well established for the design and prototyping of dental devices, guides, and technical components, and they allow reproducible dimensional planning before manufacturing [10-12].

The finalized engineering drawings were prepared in millimeters, with a default tolerance of 0.1 mm unless otherwise specified. The digital workflow allowed the spatial relationship between the three components to be verified before fabrication, including cage seating, lid clearance, and the accessibility of the chamber opening.

Design of the main body

The main body was designed as a rounded rectangular chamber with an overall external dimension of approximately 173 mm in length, 78 mm in width, and 83 mm in height. The top opening was designed to receive the internal cage and measured approximately 125 mm in internal length and 50 mm in internal width. A shallow anterior semicircular access notch was incorporated into the upper border of the body to facilitate insertion and retrieval of the internal cage.

The overall geometry of the main body was intentionally kept compact to make the unit suitable for chairside positioning. Rounded edges were adopted to avoid sharp margins, improve handling, and simplify cleaning of the external surface. The internal dimensions were selected so that the cage could seat passively within the chamber while maintaining sufficient peripheral clearance for immersion in cleansing medium.

Design of the internal cage

The internal cage was designed as a removable basket-like insert with a rounded rectangular outline. The overall dimensions of the cage were approximately 151 mm in length, 48 mm in width, and 73 mm in height. The cage walls were perforated with vertically oriented elongated slots, while the base contained multiple circular perforations arranged in a regular staggered pattern. The base perforations measured approximately 5 mm in diameter.

This perforated design was adopted to satisfy two functional needs: first, to allow rapid ingress and egress of liquid during ultrasonic activation; and second, to retain the specimens within a defined position while minimizing direct contact with the chamber walls. The use of a removable inner cage also allowed the cleansing step to be organized as a contained workflow, in which specimens could be placed, immersed, ultrasonically cleansed, and retrieved as one unit rather than being handled individually inside the chamber.

Design of the lid assembly

The lid was designed to match the outline of the main body and to provide chamber coverage during use. In its finalized form, the lid had a rounded rectangular contour with a thickness of approximately 10 mm. The corresponding top-view design showed an outer width of approximately 68 mm and a central recessed contour of approximately 48 mm. The hinge support projection measured approximately 60 mm, with an extension feature of approximately 15 mm.

The lid was intended to serve two purposes. First, it provided enclosure of the chamber during operation. Second, it preserved access and ergonomics by allowing repeated opening and closing without obstructing the

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operator. The lid-body relationship was digitally checked during CAD development to ensure that the hinge projection did not interfere with cage insertion, chamber access, or the external profile of the device.

Material selection

The prototype was finalized as a hybrid structure comprising a polycarbonate external housing and an inner stainless-steel cleansing assembly. Material selection was guided by practical requirements of dimensional stability, repeated handling, fabrication feasibility, and compatibility with routine device maintenance. Polymeric materials such as polycarbonate are well recognized in medical-device contexts and have been discussed in relation to reprocessing and material stability, while stainless-steel materials remain widely used where strength, machinability, and structural reliability are required [14,15].

For the present device, the external body was designed in polycarbonate to provide a lightweight and compact housing, whereas the internal cleansing portion and specimencontaining cage were designed in stainless steel to provide rigidity and dimensional integrity within the working chamber. Because this was a technical prototype for chairside procedural use rather than an implantable medical device, the emphasis of material selection was on structural suitability, repeated handling, and fabrication practicality rather than long-term tissue integration.

Fabrication procedure

Following completion of the CAD phase, the finalized drawings were used for prototype fabrication. The fabrication sequence consisted of:

1. generation of finalized dimensional drawings for each component;
2. fabrication of the main body according to the approved external and internal dimensions;
3. fabrication of the perforated internal cage according to the approved slot and base perforation pattern;
4. fabrication of the lid assembly with hinge-support geometry; and
5. assembly of the three components into a single working unit.

The device was fabricated as a single-chamber prototype rather than a laboratory-scale open ultrasonic bath. This decision was made to preserve compactness and simplify the intended workflow. The digital-to-physical fabrication pathway was consistent with reported uses of CAD and additive manufacturing or rapid prototyping methods in dentistry for device and component development [10-12].

Prototype assembly

After fabrication, the three components were assembled and checked for fit. The internal cage was inserted into the main body to confirm passive seating and adequate clearance from the chamber walls. The lid was then positioned and its motion relative to the main body was assessed. Assembly was considered acceptable when the following criteria were met:

(1) the cage could be inserted and removed without binding;

(2) the lid could open and close without interfering with cage placement;

(3) the device remained stable on a flat surface; and

(4) the chamber opening remained readily accessible to the operator.

No quantitative performance calibration was included in this section because the present manuscript focuses on design and fabrication of the unit rather than the subsequent bondstrength optimization experiments conducted using the device.

Preliminary functional appraisal

A bench-level functional appraisal was performed qualitatively after assembly. This appraisal focused on the usability of the device rather than on experimental outcome testing. The completed prototype was examined for overall dimensional conformity, stability, accessibility of the chamber, alignment of the lid, seating of the cage, and convenience of specimen retrieval. The perforated cage design was also visually inspected to ensure that the side-wall slots and base perforations were patent and would permit circulation of the cleansing medium around the specimens during ultrasonic use.

The intended fluid-dynamic basis for the prototype was the established action of ultrasonics in generating agitation within liquid media through acoustic streaming

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and cavitational effects, which have been widely discussed in the dental literature [13]. In the present device, this principle was translated into a confined chairside chamber intended for post-etch cleansing of ceramic specimens.

Intended use protocol

The unit was designed to be incorporated into the post-etch workflow of lithium disilicate surface conditioning. In the intended sequence, specimens would undergo HF etching and water rinsing, followed by phosphoric acid cleansing where indicated, and would then be placed within the perforated internal cage for ultrasonic-assisted cleansing before silanization and adhesive procedures. This sequence was chosen because previously published studies have shown improved residue removal and improved bonding-related outcomes when phosphoric-acid cleansing and/or ultrasonic cleaning are used after HF etching [6-9].

Ethical considerations

This section describes the design and fabrication of a prototype device only. No human participants, patient samples, or animal specimens were involved in this stage of the work; therefore, separate ethical approval was not required for the technical fabrication component.

Statistical analysis

No statistical analysis was performed for the fabrication phase because the present section describes a technical development workflow and qualitative fit-function appraisal rather than comparative experimental testing.

3. Results

The finalized prototype was developed as a compact single-chamber chairside ultrasonic postetch cleansing unit composed of three integrated components: a main body, a removable perforated internal cage, and a hinged lid assembly. The completed device showed a closed bench-top configuration with a streamlined external profile and a top-access chamber designed to receive the internal cage. This final assembly translated the original concept into a simplified chairside unit intended to support organized specimen placement, containment during cleansing, and convenient retrieval after use.

The main body was finalized as a rounded rectangular housing measuring approximately 173 mm in length, 78 mm in width, and 83 mm in height. The chamber opening measured approximately 125 mm in length and 50 mm in width and incorporated rounded terminal contours. A shallow semicircular access notch of approximately 25 mm was incorporated along the anterior margin of the opening to facilitate insertion and removal of the internal cage. The outer surface of the body was smooth and continuous, and the basal geometry provided a stable footprint for placement on a flat working surface. The upper rim of the main body was designed to support the seating relationship between the chamber and the lid, thereby contributing to the overall compact and enclosed form of the prototype.

The internal cage was fabricated as a removable basket-like insert with approximate dimensions of 151 mm in length, 48 mm in width, and 73 mm in height. It demonstrated a passive fit within the main body and could be positioned within the chamber without visible distortion or obstruction. The side walls of the cage contained elongated vertical slots arranged in two rows, while the base incorporated multiple 5-mm circular perforations distributed in a regular

staggered pattern. This perforated configuration created open pathways for cleansing solution access while simultaneously providing mechanical containment of the specimens. The cage design also enabled specimens to be handled collectively within a single insert rather than individually within the chamber, thereby improving the practicality of the cleansing workflow.

The lid assembly was completed as a rounded rectangular cover corresponding to the contour of the main body. In plan view, it measured approximately 173 mm in length and 68 mm in width, with a central recessed contour of approximately 48 mm in width. The lid thickness was approximately 10 mm, and the hinge-support extension measured approximately 60 mm with an additional projecting segment of approximately 15 mm. When positioned over the main body, the lid covered the chamber opening without interfering with the seated cage. Visual assessment of the assembled unit showed satisfactory alignment between the lid and the body margins, and the hinge arrangement permitted repeated opening and closing while maintaining access to the chamber.

Following fabrication, the three components were assembled into a single functional prototype. The internal cage could be inserted into and removed from the chamber without binding, and the lid could be opened and repositioned without interfering with the cage or

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chamber rim. In the closed position, the lid covered the opening in a stable manner and preserved the compact external profile of the device. The final assembled unit therefore demonstrated a coherent relationship between body, cage, and lid, with each component fulfilling its intended structural and operational role.

From a functional standpoint, the completed prototype incorporated several design features that supported its intended chairside use. The single-chamber configuration reduced bulk and simplified the overall architecture when compared with a more complex multi-component arrangement. The removable perforated cage enabled grouped placement and retrieval of specimens, while the side-wall slots and base perforations allowed direct communication between the specimen compartment and the surrounding cleansing medium. The rounded external and internal contours contributed to the compact form of the device, and the hinged lid provided enclosure during operation while preserving ease of access during specimen loading and unloading.

Overall, the fabrication phase resulted in a completed compact prototype of a chairside ultrasonic post-etch cleansing unit with reproducible CAD-defined geometry and a three-part assembly consisting of a main body, perforated cage, and lid. The assembled device fulfilled the predefined design objectives of compactness, specimen containment, removable internal support, and accessible covered chamber design. No structural incompatibility between the fabricated components was observed during assembly, and the prototype was considered suitable for integration into the planned post-etch cleansing workflow for hydrofluoric acidetched lithium disilicate specimens.

Discussion

The present technical report was undertaken to translate an evidence-supported but operationally under-standardized laboratory step into a dedicated chairside device. Existing studies on lithium disilicate have consistently shown that the condition of the etched ceramic surface is not determined by hydrofluoric acid treatment alone, but also by how effectively postetch reaction products are removed before silanization and resin bonding [6-9]. In particular, post-etch cleaning protocols incorporating phosphoric acid and ultrasonic cleansing have been associated with cleaner ceramic surfaces, reduced fluoride-associated residues, and improved bond-related outcomes when compared with HF treatment alone [6-9]. However, these protocols have largely been performed with conventional laboratory ultrasonic baths rather than with devices specifically designed for this application. The present unit was therefore conceived not as a replacement for the established chemistry of ceramic bonding, but as a purpose-built platform intended to deliver the ultrasonic cleansing step in a more compact, contained, and reproducible manner.

A central design decision in the present study was the adoption of a single-chamber compact architecture. This simplification was intentional. In a chairside setting, added compartments and handling steps can increase bulk, complicate manipulation, and reduce workflow clarity. By reducing the unit to a main body, a removable perforated cage, and a lid assembly, the prototype aimed to preserve only the essential functions required for post-etch cleansing: specimen containment, liquid access, chamber coverage, and straightforward retrieval. This approach is consistent with the broader movement in digital prosthodontics toward streamlined chairside systems that prioritize efficiency, reproducibility, and integration into clinical routines [16,17]. Within that context, the present device represents a focused technical adaptation of chairside design principles to a niche but clinically relevant adhesive procedure.

The perforated internal cage was one of the defining structural features of the prototype. Its function was not merely mechanical containment, but also facilitation of fluid exchange around the ceramic specimens during ultrasonic activation. Ultrasonics are understood to act through mechanisms such as acoustic streaming and cavitational activity, both of which depend on effective interaction between the vibrating energy field and the surrounding liquid medium [13]. For that reason, an enclosed but non-perforated holding insert would have conflicted with the intended working principle of the cleansing step. The elongated side slots and perforated base were therefore incorporated to maintain open pathways for solution movement while minimizing uncontrolled specimen displacement within the chamber. In practical terms, this design may help make the cleansing step more consistent by allowing multiple specimens to be handled within a defined insert rather than loose within a bath. Although this functional rationale is sound, quantitative confirmation of flow behavior and energy distribution within the chamber remains a subject for future investigation.

Another important aspect of the present work was the use of a CAD-based design workflow. Digital design allowed

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the geometry of the body, cage, and lid to be planned, revised, and dimensionally coordinated before fabrication. This is particularly advantageous in device development, where even minor modifications in chamber opening, internal clearance, or lidbody relationship can affect usability. The use of CAD and digitally driven manufacturing approaches has become increasingly common across dentistry for restorations, guides, appliances, and custom technical components because it improves reproducibility and facilitates iterative refinement [10-12,18]. In the present study, the CAD workflow also served an additional methodological role: it converted the device from a conceptual idea into a reproducible geometry that can be described, fabricated, and modified in a standardized way. That reproducibility is especially important if future studies aim to compare cleansing performance across different chamber volumes, perforation patterns, or operating parameters.

The material strategy adopted in the prototype also reflected the intended use of the device. The combination of a polycarbonate external housing with an internal metallic cleansing assembly was selected to balance compactness, structural support, and practical handling during repeated bench or chairside use [14,15]. In a prototype designed for procedural standardization rather than permanent intraoral service, the outer housing primarily functions as an ergonomic and protective shell, whereas the internal chamber and cage must preserve shape and positional stability during use. This separation of roles is advantageous because it allows the working chamber to remain mechanically robust while the outer body remains lightweight and compact. At the same time, this prototype-stage configuration should not be interpreted as final clinical product validation. Material durability under repeated chemical exposure, sealing performance, thermal behavior during operation, ease of decontamination, and long-term maintenance requirements were beyond the scope of the present report and require dedicated testing before wider translational use can be considered.

A notable strength of this study is that it addresses a translational gap rather than only a laboratory variable. Much of the current literature on lithium disilicate bonding focuses on whether a given surface-treatment sequence improves bond strength or surface morphology [29]. Fewer reports address how such protocols can be converted into practical, repeatable chairside workflows. In that sense, the present device should be viewed as an enabling platform: it does not itself prove superiority of one cleansing protocol over another, but it creates the means to standardize the delivery of ultrasonic-assisted cleansing in a dedicated and reproducible format. This distinction is important, because technical development studies in dentistry often precede full biological and clinical validation. Similar phased adoption has been reported for other digitally designed dental devices and appliances, where feasibility and workflow definition are established first, followed by functional and clinical evaluation [16-18].

The limitations of the present report should be acknowledged clearly. First, the study was restricted to design, fabrication, assembly, and qualitative fit-function appraisal; it did not quantify ultrasonic frequency, power delivery, cavitation field, acoustic streaming pattern, or intrachamber temperature rise during use. Second, no direct comparison was made between the fabricated prototype and a conventional laboratory ultrasonic bath. Third, the present report did not evaluate long-term dimensional stability, resistance to repeated cleansing cycles, leakage, or operator-centered variables such as handling time and ease of maintenance. Finally, because the work was conceived as a technical report, it cannot by itself establish clinical benefit. Future studies should therefore examine the chamber's acoustic behavior, optimize the working solution volume and specimen positioning, monitor temperature changes during operation, and compare residue removal and bonding outcomes against established laboratory cleansing methods using SEM, EDS, profilometry, and bond-strength testing. These next steps are particularly important because the digital literature itself has emphasized that technological development in dentistry often advances faster than high-level clinical validation [16].

Within these limitations, the present study demonstrates that fabrication of a compact, dedicated chairside ultrasonic post-etch cleansing unit is technically feasible. The resulting prototype incorporated a simplified single-chamber layout, a removable perforated internal cage, and a hinged lid assembly, all of which were directed toward specimen organization, liquid access, and procedural consistency. From a manuscript standpoint, the main contribution of this work is not merely the fabrication of a new device, but the proposal of a standardized technical solution for a cleansing step that has already shown relevance in the lithium disilicate bonding literature. If subsequent validation studies

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confirm adequate cleaning efficacy, thermal safety, and workflow reliability, such a device may offer a practical route for bringing ultrasonic post-etch cleansing closer to routine chairside implementation [6-9,16,17].

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