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*IZVORNI ZNANSTVENI RAD*

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# Apical Irrigant Extrusion Using Two Er:YAG Laser Irrigation Modes with Three Types of Laser Tips

# *Apikalno protiskivanje sredstva za ispiranje pri uporabi lasera Er:YAG na dva načina rada s trima različitim laserskim nastavcima*

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**Abstract**
The aim of this study was to evaluate the amounts of apically extruded 3% sodium hypochlorite using two modes of Er:YAG laser-activated irrigation (LAI), super short pulse (SSP) and shock wave enhanced emission photoacoustic streaming (SWEEPS®) by combining three types of laser tips (FT) and conventional syringe needle irrigation (SNI). **Methods:** Twenty extracted human maxillary central incisors were prepared using Reciproc® instruments (size 40, taper 0.06). The irrigant volumetric flow (IVF) was accurately standardized using a precision syringe pump with constant irrigant delivery through the 27G needle. The tested irrigation protocols (60 s) were groups 1: 27-G SNI with 0.05 ml/s constant IVF; group 2: SSP (10 mJ, 15 Hz, pulse duration 50 μs) + Radial SWEEPS FT; group 3: SSP + photon-induced photoacoustic streaming (PIPS) FT; group 4: SSP+SWEEPS FT; group 5: AutoSWEEPS (20 mJ, 15 Hz, pulse duration 25 μs) + Radial SWEEPS FT; group 6: AutoSWEEPS+PIPS FT; group 7: AutoSWEEPS+SWEEPS FT. Each protocol was evaluated in 10 repetitions each. Apically extruded irrigant was collected, and net weighted. **Results:** There were significantly lower amounts of extruded irrigant with SNI and SSP using radial SWEEPS and PIPS FTs compared to the other tested laser protocols ($p<0.05$). In the AutoSWEEPS groups, all three FTs had similar amounts of extruded irrigant ($p>0.05$). **Conclusion:** In straight root canals, the use of various fiber FTs in the AutoSWEEPS mode exhibited a higher potential for irrigant extrusion.

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## Introduction

Root canal irrigation aims to completely clean the complex root canal system of remaining vital or necrotic pulp tissue, bacterial biofilms, infected debris, and smear layers [1] to provide conditions for initiating the healing of periapical lesions [2]. The efficacy of irrigation depends on the antimicrobial properties of the irrigant, its ability to safely reach the deepest part of the root canal, and the intracanal complexities in which bacterial biofilms are firmly attached to dentinal walls [3]. Therefore, ensuring a sufficient irrigant flow rate and dynamic irrigant exchange in the deepest part of the root canal is essential [4].

## Uvod

Svrha irigacije korijenskog kanala jest potpuno ukloniti preostalo vitalno ili nekrotično tkivo pulpe, biofilmove i inficirane ostatke iz složenoga sustava korijenskih kanala [1] kako bi se osigurali uvjeti za početak cijeljenja periapikalnih lezija [2]. Učinkovitost ispiranja ovisi o antimikrobnim svojstvima iriganasa, njegovoj mogućnosti da prodre u najskrovitije i najdublje dijelove korijenskog sustava kanala gdje su biofilmovi čvrsto pričvršćeni za stijenke dentina [3]. Zato je ključno osigurati dovoljnu brzinu protoka iriganasa i njegovu dinamičku izmjenu, osobito u apikalnoj trećini korijenskog kanala [4].

Syringe needle irrigation (SNI) is the most common technique in which a needle is positioned stationary in the root canal during irrigant delivery. The efficacy of SNI depends on the depth of the needle placed in the root canal, the available space in the apical third, and the irrigant flow rate [4, 5, 7]. Although SNI is generally effective for simple root canal morphologies [4], it faces significant limitations in complex intracanal anatomies. The primary issues are inadequate hydrodynamic turbulence, which impedes the effective penetration of the irrigant and fails to provide sufficient chemo-mechanical cleaning [7, 8]. As a result, bacteria and infected debris may persist in challenging areas such as isthmuses, lateral canals, and apical thirds [9, 10, 27]. Therefore, various activated irrigation techniques have been recommended and studied.

Laser-activated irrigation (LAI) is an excellent choice for improving root canal cleaning and disinfection, showing excellent results in debris and smear layer removal [11], vital pulp removal [12], and biofilm removal [13,14]. Irrigants within the root canal system absorb Er: YAG laser wavelengths, producing powerful interactions at very low energy. The cleaning mechanism of LAI is based on optic cavitation and high fluid speed in the irrigant caused by the expansion and implosion of laser-induced bubbles created at the tip of the laser fiber [15, 16]. In the conventional LAI approach, the laser fiber tip (FT) is positioned inside the canal approximately 5 mm from the apical foramen, and the pulse energies are >30 mJ and up to 250 mJ [16]. On the other hand, photon-induced photoacoustic streaming (PIPS), is characterized by a conical laser tip positioned in the pulp chamber, a lower pulse energy of 20 mJ, and a super short pulse (SSP) duration (50 µs). This approach creates fast vertical fluid movement throughout the root canal, especially in the apical region, resulting in biofilm detachment and coronal displacement [17–19].

The shock wave-enhanced emission photoacoustic streaming (SWEEPS) modality of the Er: YAG laser has been introduced to enhance the cavitation effect in the constrained space of the root canal. The specificity of the SWEEPS modality is that the Er: YAG laser emits pairs of pulses, accelerating the collapse of primary bubble by forming a second bubble. As the second bubble grows, the additional pressure causes the first bubble to collapse, emitting primary and secondary shock waves deeper within the endodontic space [20]. Furthermore, the pulse duration in the SWEEPS modality is twice longer than that of the SSP modality (25 µs), doubling the peak power of the pulse. Given the much stronger pulses, the safety of SWEEPS regarding irrigant extrusion has been justifiably questioned. The SSP mode of Er: YAG LAI is safer than SNI [21] and causes less postoperative pain after primary root canal treatment compared with ultrasonic-activated irrigation [22]. In addition, Jezeršek et al. [24] reported that the SSP and AutoSWEEPS modes caused less extrusion, regardless of the laser energy than open-ended SNI. However, the pressure along the depth of the root canal appears to depend on the laser modality and FT design [25]. FTs for SSP and AutoSWEEPS LAI are rigid and can be conical, radial, or flat-ended, resulting in different laser energy emission pat-

Ispiranje iglom i štrcaljkom (SNI) najčešća je tehnika irigacije u kojoj je igla nepomično postavljena u korijenski kanal tijekom primjene iriganse. Učinkovitost SNI-ja ovisi o dubini insercije igle u korijenskom kanalu, raspoloživom prostoru u apikalnoj trećini i brzini protoka iriganse [4, 5, 7]. Iako je SNI općenito učinkovit ako je morfologija korijenskog kanala jednostavna [4], postoje mnogobrojna ograničenja kad je riječ o toj metodi u slučaju složenih intrakanalnih anatomija. Primarni su problemi neadekvatna hidrodinamična turbulencija koja onemogućuje učinkovito prodiranje iriganse i ne osigurava učinkovito kemomehaničko čišćenje [7, 8]. Kao rezultat toga bakterije i detritus mogu perzistirati u područjima kao što su istmusi, lateralni kanali i apikalne trećine [9, 10, 27]. Zato se preporučuju i proučavaju različite tehnike aktivirane irigacije.

Laserski aktiviranom irigacijom (LAI) postižu se odlični rezultati u čišćenju i dezinfekciji korijenskih kanala [11] te u uklanjanju vitalne pulpe [12] i biofilma [13, 14]. Sredstva za ispiranje unutar sustava korijenskog kanala apsorbiraju valne duljine lasera Er:YAG. Mehanizam LAI-ja temelji se na optičkoj kavitaciji i velikoj brzini fotoakustičnog strujanja iriganse prouzročenoj ekspanzijom i implozijom laserom induciranih mjehurića stvorenih na vrhu laserskoga nastavka [15,n16]. U konvencionalnom pristupu mehanizmom LAI-ja vrh laserskoga vlakna (FT) postavljen je unutar kanala približno 5 mm od apikalnog foramena, a energije pulsa su > 30 mJ i do 250 mJ [16]. S druge strane, fotoakustično strujanje izazvano fotonima (PIPS) podrazumijeva konusni laserski nastavak smješten u pulpnoj komori, energiju pulsa manju od 20 mJ i trajanje superkratkoga pulsa (SSP) (50 µs). Tim pristupom stvara se brzo okomito prodiranje tekućine kroz korijenski kanal, posebno u apikalnoj trećini, što rezultira odvajanjem biofilma i njegovim koronarnim pomakom [17 – 19].

Način rada fotoakustičnog strujanja emisije pojačanog udarnim valom (SWEEPS) lasera Er:YAG uveden je da bi se pojačao učinak kavitacije u ograničenom prostoru korijenskog kanala. Specifičnost modaliteta SWEEPS-a jest da laser Er:YAG, ubrzavajući kolaps primarnoga mjehurića formiranjem drugoga, emitira parove impulsa. Kako drugi mjehurić raste, tako dodatni pritisak potiče kolaps prvog mjehurića, emitirajući primarne i sekundarne udarne valove dublje unutar endodontskog prostora [20]. Nadalje, trajanje impulsa u modalitetu SWEEPS dvostruko je dulje od modaliteta SSP (25 µs), udvostručujući snagu impulsa. S obzirom na mnogo jače impulse opravdano je dovedena u pitanje sigurnost SWEEPS-a kad je riječ o protiskivanju iriganse kroz apikalni otvor u periapikalna tkiva. SSP način Er:YAG LAI sigurniji je od SNI-ja [21] i uzrokuje manju postoperativnu bol poslije primarnoga liječenja korijenskog kanala u usporedbi s ultrazvučno aktiviranom irigacijom [22]. Nadalje, Jezeršek i suradnici [24] izvijestili su da SSP i AutoSWEEPS uzrokuju manje istiskivanja iriganse, bez obzira na energiju lasera u usporedbi s konvencionalnim metodama irigacije (s vršno otvorenom iglom). No čini se da na porast tlaka u korijenskom kanalu utječe laserski način rada i dizajn FT-a [25]. FT-ovi za SSP i AutoSWEEPS LAI su kruti. Mogu biti konični, radijalni ili ravni, što rezultira različitim oblicima odašiljanja terns [19, 26]. Burklein et al. [26] concluded that FT design might influence the cleaning efficacy of LAI, and their effectiveness in root canal treatment is still being investigated [12, 19]. However, it is still unclear which FT should be used for SSP and SWEEPS modes, considering the safety of application without irrigant extrusion.

The present study aimed to evaluate and compare apical irrigant extrusion during the SSP and AutoSWEEPS modes of Er: YAG LAI using three different FTs: PIPS FT, radial conical FT, and SWEEPS sapphire conical FT. The null hypotheses were that there were no differences (a) in the amount of extruded irrigant between the SSP and AutoSWEEPS modes of Er: YAF LAI and (b) between different FTs regardless of the mode used.

## Materials and Methods

### Sample selection and preparation

Twenty human maxillary central incisors, extracted for periodontal reasons, were collected and stored in 3% NaOCl until the time of the experiment. The root canal morphology was verified radiographically and with cone beam computed tomography scanning (Cranex 3DX; Soredex, Tuusula, Finland) using the following parameters: field of view, 5 9 5 (5.0 mm) mm; ENDO, 85 µm; 6.3 mA; 90 kV; and 8.7 s. Samples with any of the following parameters were excluded: root fracture, incomplete apexogenesis, signs of internal or external resorption, calcification, or lateral canals.

After creating the access cavities, the working length was standardized to 20 mm by decoronating the excess tooth structure while maintaining a fully accessible cavity. Root canal instrumentation was performed using a reciprocating instrument, Reciproc® R40 (0.06/variable taper; VDW Dental, München, Germany). During instrumentation, 5 ml of 3% NaOCl was used. The patency of the root canal was checked with an ISO K-file #10. After root canal preparation, the prepared samples were sterilized in an autoclave (15 min, 121°C, 20 psi).

Each sample was embedded in an acrylic mold in the middle part of the root, and the root tip was attached to a 10 mm-long drainage tube (Discofix Cluer lock, B. Braun Melsungen AG 34209 Melsungen, Germany). This attachment was double sealed with flowable composite (Gaenial Universal Injectable, GC, Tokyo, Japan) and wax to prevent premature leakage of the irrigant. The prepared teeth were positioned horizontally on the system. A supplier needle (27 G open-notched, DiaDent; Netherland) was connected to the syringe mounted on a precision syringe pump (Aladdin, World Precision Instruments, Sarasota, FL, USA) to ensure accurate irrigant volumetric flow (IVF). The apically extruded irrigant was collected and weighed (g) using a microbalance (TW423L, Shimadzu, Tokyo, Japan), after which the mass of the measuring cup was subtracted. This experimental model was precisely described and shown in research of Vidas et al. [21].

laserske energije [19, 26]. Burklein i suradnici [26] zaključili su da dizajn FT-a može utjecati na učinkovitost čišćenja [12, 19]. Unatoč mnogobrojnim spoznajama još uvijek nije jasno kojim se FT-om treba koristiti za načine rada u modalitetima SSP i SWEEPS, s obzirom na sigurnost primjene bez protiskivanja iriganasa.

Cilj ovog istraživanja bio je procijeniti i usporediti apikalno protiskivanje iriganasa tijekom načina rada u modalitetu SSP i AutoSWEEPS lasera Er:YAG koristeći se trima različitim laserskim nastavcima: PIPS FT-om, radijalnim konusnim FT-om i safirnim konusnim SWEEPS FT-om. Nulte su hipoteze da nema razlike (a) u količini apikalno protisnutoga iriganasa između načina rada korištenjem SSP-a i AutoSWEEPS-a_ i (b) između različitih laserskih nastavaka bez obzira na korišteni način rada lasera.

## Materijali i metode

### Odabir i priprema uzoraka

Dvadeset humanih maksilarnih središnjih sjekutića, izvađenih iz parodontnih razloga, prikupljeno je i pohranjeno u 3-postotni NaOCl do početka eksperimenta. Morfologija korijenskog kanala potvrđena je radiografski i s pomoću CBCT-a (Cranex 3DX; Soredex, Tuusula, Finska) korištenjem sljedećih parametara: vidno polje, 5 9 5 (5,0 mm) mm; ENDO, 85 µm; 6,3 mA; 90 kV; i 8,7 s. Uzorci s nekima od sljedećih znakova isključeni su iz studije: fraktura korijena, nepotpuna apeksogeneza, znakovi unutarnje ili vanjske resorpcije, kalcifikacija ili lateralni kanali.

Nakon izrade pristupnih kaviteta radna duljina korijenskih kanala standardizirana je na 20 mm skraćivanjem krune zuba, uz uvjet da je potpuno očuvan pristupni kavitet. Instrumentacija korijenskih kanala obavljena je recipročnim instrumentima Reciproc® R40 (0,06/varijabilni konus; VDW Dental, München, Njemačka). Tijekom instrumentacije korišteno je 5 mL 3-postotnoga natrijeva hipoklorita. Prohodnost korijenskog kanala provjerena je ISO K-instrumentom #10. Nakon pripreme korijenskog kanala pripremljeni uzorci sterilizirani su u autoklavu (15 min., 121 °C, 20 psi).

Svaki uzorak je središnjim dijelom korijena umetnut i pričvršćen u akrilni kalup, na vrh korijena pričvršćena je drenažna cijev duga 10 mm (Discofix Cluer lock, B. Braun Melsungen AG 34209 Melsungen, Njemačka). Taj je spoj dvostruko zabrtvljen tekućim kompozitom (Gaenial Universal Injectable, GC, Tokyo, Japan) i voskom da bi se spriječilo prerano istjecanje iriganasa. Preparirani zubi postavljeni su vodoravno na eksperimentalni model. Irigacijska igla (27 G, vršno otvorena, DiaDent; Nizozemska) spojena je na štrcaljku umetnutu na preciznu irigacijsku pumpu (Aladdin, World Precision Instruments, Sarasota, FL, SAD) kako bi se osigurao konstantni volumetrijski protok iriganasa (IVF). Apikalno protisnuti irigans skupljen je i izvagan (g) s pomoću mikrovage (TW423L, Shimadzu, Tokio, Japan), nakon čega je oduzeta masa mjerne posude. Taj eksperimentalni model precizno je opisan i prikazan u istraživanju Vidasa i suradnika [21].

## Irrigation protocols and extruded irrigant measurements

In group 1 (control group), the root canal irrigation was performed using SNI with a 27-G needle (Appli-Vac; Vista Dental, WI, USA) placed in the access cavity at the previously determined level, and 3% NaOCl was used at an IVF rate of 0.05 ml/s. The protruded irrigant was collected into a measuring cylinder and weighed (g), subtracting the weight of the measuring cylinder using a microbalance (TW423L, Shimadzu, Tokyo, Japan). Before each sampling, the measuring cylinder was completely dried.

The sequence of irrigation procedures for each sample was assigned using randomization software (random.org). Each tooth served as its own negative control by measuring the irrigant extrusion during passive irrigation with the supplier needle placed in the access cavity. The samples were positioned horizontally so that the influence of gravitation on extrusion could be avoided.

In six other groups (G2-G7) (Table 1), LAI was performed using the Er:YAG laser with a wavelength of 2940 nm (Lightwalker AT, Fotona, Ljubljana, Slovenia) in two laser modes: in G2-G4, the SSP mode (20 mJ, 15 Hz, pulse duration 50 µs); in G5-G7, the Auto SWEEPS mode (20 mJ, 15 Hz, pulse duration 25 µs, temporal separation between pulses varied from 300–600 µs with 10 µs steps). Three different laser tips were used for each laser mode: a radial SWEEPS (600/14, Fotona) (Fig. 1) (G2 and G5), a PIPS (600/9, Fotona) (Fig.1) (G3 and G6), and a SWEEPS sapphire tip (Figure 1) (600/8, Fotona) (G4 and G7). FTs were mounted on an H14-N handpiece with 90° angulation and an integrated air/water spray nozzle. During the measurement of the extruded irrigant, the water spray and air were turned off.

## Irigacijski protokol i mjerenje protisnutog iriganse

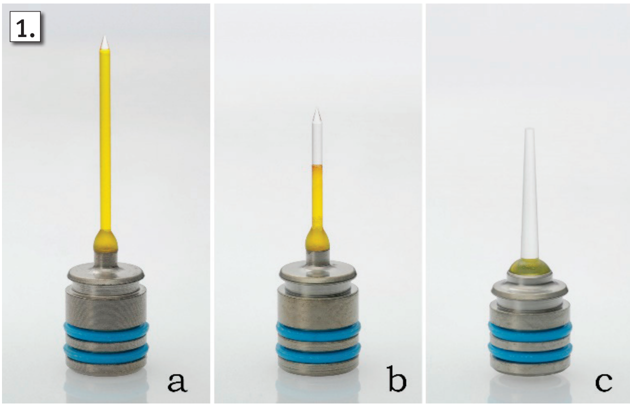
U skupini 1 (kontrolna skupina) irigacija korijenskog kanala provedena je s pomoću SNI-ja iglom 27-G (Appli-Vac; Vista Dental, WI, SAD) postavljenom u pristupni kavitet na prethodno određenoj razini. Korišten je 3-postotni NaOCl pri IVF brzini od 0,05 mL/s. Protisnuti irigans prikupljen je u mjernu posudicu i izvagan (g), oduzimajući težinu mjerne posudice s pomoću mikrovage (TW423L, Shimadzu, Tokio, Japan). Prije svakog uzorkovanja mjerna je posudica bila potpuno osušena.

Redoslijed irigacijskih protokola za svaki uzorak je dodijeljen s pomoću softvera za nasumično odabiranje (random.org). Svaki je zub služio kao vlastita negativna kontrola mjerenjem protisnutog iriganse tijekom pasivne irigacije s irigacijskom iglom postavljenom u pristupni kavitet. Uzorci su postavljeni vodoravno da bi se izbjegao utjecaj gravitacije na ekstruziju.

U preostalih šest grupa (G2 – G7) (tablica 1.) LAI je proveden korištenjem lasera Er:YAG valne duljine 2940 nm (Lightwalker AT, Fotona, Ljubljana, Slovenija) na dva načina rada: u G2 – G4 primijenjen je SSP mod (20 mJ, 15 Hz, trajanje impulsa 50 µs), a u G5 – G7 Auto SWEEPS (20 mJ, 15 Hz, trajanje impulsa 25 µs, vremenski razmak između impulsa varirao je od 300 do 600 µs s prekidima od 10 µs). Za svaki način rada lasera korištena su tri različita laserska nastavka: radijalni SWEEPS (600/14, fotona) (slika l. 1) (G2 i G5), PIPS (600/9, fotona) (slika 1.) (G3 i G6), SWEEPS sa safirnim vrškom (slika 1.) (600/8, fotona) (G4 i G7). FT-ovi su postavljeni na H14-N ručni dio lasera pod kutom od 90° i integriranom mlaznicom za raspršivanje zraka i vode. Tijekom mjerenja bili su isključeni vodeni sprej i zrak.

**Table 1** Description of the irrigation protocol groups
**Tablica 1.** Značajke testiranih irigacijskih protokola

| Group | Irrigation method | Fiber tip | IVF/duration | Laser parameters |
|---|---|---|---|---|
| G1 | Needle 27-gauge irrigation | - | constant IVF, 0.05 ml/s, 60 s | - |
| G2 | SSP mode | Radial SWEEPS | constant IVF, 0.05 ml/s, 60 s | 2940 nm 15 Hz, 20 mJ, 60 s, pulse duration 50 µs |
| G3 | SSP mode | PIPS | constant IVF, 0.05 ml/s, 60 s | 2940 nm 15 Hz, 20 mJ, 60 s, pulse duration 50 µs |
| G4 | SSP mode | SWEEPS sapphire | constant IVF, 0.05 ml/s, 60 s | 2940 nm 15 Hz, 20 mJ, 60 s, pulse duration 50 µs |
| G5 | AutoSWEEPS mode | Radial SWEEPS | constant IVF, 0.05 ml/s, 60 s | 2940 nm 15 Hz, 20 mJ 60 s, pulse duration-2x25 µs (varied delay 300–600 µs) |
| G6 | AutoSWEEPS mode | PIPS | constant IVF, 0.05 ml/s, 60 s | 2940 nm 15 Hz, 20 mJ 60 s, pulse duration-2x25 µs (varied delay 300–600 µs) |
| G7 | AutoSWEEPS mode | SWEEPS sapphire | constant IVF, 0.05 ml/s, 60 s | 2940 nm 15 Hz, 20 mJ 60 s, pulse duration-2x25 µs (varied delay 300–600 µs) |



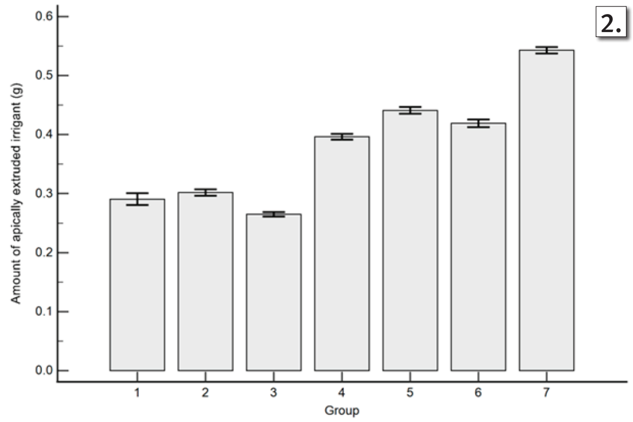




**Figure 1** Laser fiber tips used in the study: a. Radial shock wave-enhanced emission photoacoustic streaming (SWEEPS FT) (600/14); b. photon-induced photoacoustic streaming (PIPS FT) (600/9); c. SWEEPS sapphire FT (600/8)

**Slika 1.** Laserski nastavci korišteni u istraživanju: a. Fotoakustično strujanje emisijom radijalnog udarnog vala (SWEEPS FT) (600/14); b. Fotoakustično strujanje izazvano fotonima (PIPS FT) (600/9); c. SWEEPS safirni laserski nastavak (600/8)

**Figure 2** The amount of apically extruded irrigant (g) during the tested irrigation techniques: NI-needle irrigation (group 1) (0.29±0.01); group 2- SSP/radial SWEEPS FT(0.31±0.01); group 3-SSP/PIPS FT(0.26±0.01); group 4-SSP/sapphire SWEEPS FT (0.39±0.01); group 5-AutoSWEEPS/radial SWEEPS FT(0.44±0.01); group 6-AutoSWEEPS/PIPS FT(0.41±0.01); group 7-AutoSWEEPS/sapphire SWEEPS FT(0.54±0.01).

**Slika 2.** Količina apikalno protisnutoga irigansa (g) tijekom testiranih irigacijskih protokola: NI-needle irrigation (group 1) (0.29±0.01); group 2- SSP/radial SWEEPS FT(0.31±0.01); group 3-SSP/PIPS FT(0.26±0.01); group 4-SSP/sapphire SWEEPS FT (0.39±0.01); group 5-AutoSWEEPS/radial SWEEPS FT(0.44±0.01); group 6-AutoSWEEPS/PIPS FT(0.41±0.01); group 7-AutoSWEEPS/sapphire SWEEPS FT(0.54±0.01)

During LAI, FTs were placed in the access cavity above the root canal orifices, which had been filled with NaOCl. The central position of the FTs during LAI was controlled under magnification of 16× (M320 microscope; Leica Microsystems, Wetzlar, Germany), although with the AutoSWEEPS mode, the FT did not have to be positioned in the middle of the access cavity. To avoid potential iatrogenic damage of samples, each tooth was checked after each particular protocol which was a mandatory step before the FT or the irrigation needle positioning. On each tooth sample seven different endodontic irrigation protocols were performed (10 measurements for each protocol, in total 70 measurements per tooth). A 30-s pause was made between each measurement. Each irrigation procedure lasted for 60 seconds. Before each test, the entire system was filled with an irrigant solution so that the entrapped air bubbles could be eliminated.

### Statistical analysis

The data were analyzed using IBM SPSS 26 statistical software. The data were analyzed using the Friedman's two-way analysis of variance and the Dunn's pairwise test to identify the differences in individual groups. A significance level of 0.05 was used.

## Results

The amount of extruded irrigant is shown in Figure 2. The volume of extruded irrigant was significantly lower in the G1 and two SSP groups (G2 and G3), than in the G4–G7 groups ($p<0.05$). There were no significant differences between G1, G2 (SSP/SWEEPS radial), and G3 (SSP/PIPS) ($p=0.2$, $p=0.464$). SSP/SWEEPS FT (G4) caused NaOCl extrusion similar to AutoSWEEPS/PIPS FT (G6) ($p=0.289$).

Tijekom LAI-ja FT-ovi su bili postavljeni u pristupni kavitet ispunjen natrijevim hipokloritom iznad ulaza u korijenski kanal. Središnji položaj FT-ova tijekom LAI-ja kontroliran je pod povećanjem od 16 puta (M320 mikroskop; Leica Microsystems, Wetzlar, Njemačka), iako s načinom rada u modalitetu AutoSWEEPS, FT nije nužno morao biti postavljen u sredinu pristupne šupljine. Da bi se izbjeglo potencijalno ijatrogeno oštećenje uzoraka, svaki je zub provjeren nakon svakoga protokola što je ujedno bio i obvezan korak prije svakoga sljedećeg pozicioniranja FT-a ili irigacijske igle. Na svakom uzorku zuba provedeno je sedam različitih irigacijskih protokola (10 mjerenja za svaki protokol, ukupno 70 mjerenja po zubu). Između svakog mjerenja bila je stanka od 30 sekunda. Svaki irigacijski postupak trajao je 60 sekunda. Prije svakog mjerenja cijeli je irigacijski sustav ispunjen irigansom da bi se eliminirali zarobljeni mjehurići zraka.

### Statistička analiza

Statistička analiza provedena je u softveru IBM SPSS 26. Podatci su analizirani Friedmanovom dvosmjernom analizom varijance i Dunnovim parnim testom kako bi se utvrdile razlike u pojedinim skupinama. Korištena je razina značajnosti od 0,05.

## Rezultati

Količina ekstrudiranoga iriganса prikazana je na slici 2. Volumen protisnutoga iriganса bio je značajno niži u G1 i dvjema SSP skupinama (G2 i G3), nego u G4 – G7 skupinama ($p < 0,05$). Nije bilo značajnih razlika između G1, G2 (SSP/SWEEPS radijalno) i G3 (SSP/PIPS) ($p = 0,2$, $p = 0,464$). SSP/SWEEPS FT (G4) prouzročio je protiskivanje natrijeva hipoklorita slično AutoSWEEPS/PIPS FT-u (G6)

In the AutoSWEEPS group, all the FTs caused similar extrusion of NaOCl ($p>0.05$).

In the SSP groups, the greatest extrusion was found with the SWEEPS sapphire tip (0.39±0.01) ($p<0.05$) followed by the PIPS FT (0.26±0.01) and radial SWEEPS tips (0.30±0.01), which did not differ significantly ($p>0.05$). In the AutoSWEEPS group, the PIPS FT caused the least extrusion (0.41±0.01), and the SWEEPS sapphire FT caused the highest extrusion (0.54±0.01); however, no significant differences among the FTs were observed ($p=0.002$).

When comparing the extrusion of NaOCl with different modes but the same FTs, the SSP mode generally produced significantly less irrigant extrusion ($p<0.05$). Group G7 (AutoSWEEPS/SWEEPS FT) had the highest irrigant extrusion (0.54±0.01), whereas group G3 (SSP/PIPS FT) had the lowest extrusion rate (0.26±0.01).

## Discussion

The clinical success of endodontic irrigation depends on achieving a balance between irrigation efficiency and safety—specifically, preventing irrigant extrusion. The LAI is already established as a safe and effective method for endodontic irrigation. The aim of this research was to compare the extrusion potential during different irrigations in different LAI techniques based on measured extrusions, rather than its clinically relevant extrusion. Accordingly, the apical foramen was intentionally left open. This methodological setup reflects the absence of studies providing definitive values for periapical pressure, as highlighted and discussed in the text.

The findings of this study showed that the apical extrusion of NaOCl was different among different LAI protocols and FTs; hence, the null hypotheses (a) and (b) can be rejected. The research clearly illustrates the dependency between the type of FT used and the laser modality on the extent of irrigation extrusion on *ex vivo* model. The shape and size of the FT play a crucial role in influencing bubble formation during LAI [28]. Regardless of the specific LAI mode used in this research, whether SSP or AutoSWEEPS, the lowest level of extrusion was observed with the PIPS FT, while the highest extrusion was recorded with the SWEEPS sapphire FT. Although all FTs used had the same diameter, the PIPS FT (600/9) differs with its conical shape and 5 mm-long cleavage from the tip. This unique construction facilitates the formation of spherical cavitation bubbles that predominantly expand laterally rather than apically, thereby potentially reducing apical extrusion. In contrast, the gradually conical design of sapphire SWEEPS and flat FTs tends to generate channel-like bubbles that are more likely to extend apically, increasing the risk of greater apical extrusion [29]. These differences in bubble dynamics significantly influence the amount of extruded irrigant, as they directly relate to the pressure generated within the root canal during LAI. Our goal was not to present results which would recommend particular protocol, but to provide data which can enhance the guidelines for more precise and successful LAI clinical protocols in the future.

($p = 0,289$). U skupini AutoSWEEPS svi su FT-ovi prouzročili slično protiskivanje natrijeva hipoklorita ($p > 0,05$).

U skupinama SSP-a najveće je protiskivanje iriganasa utvrđeno kod laserskoga nastavka SWEEPS sa safirnim vrškom (0,39 ± 0,01) ($p < 0,05$), zatim PIPS FT-a (0,26 ± 0,01) i radijalnih nastavaka SWEEPS-a (0,30 ± 0,01) koji se nisu značajno razlikovali ($p >0,05$). U skupini AutoSWEEPS, PIPS FT prouzročio je najmanje protiskivanje iriganasa (0,41 ± 0,01), a laserski nastavak SWEEPS sa safirnim vrškom najveće (0,54 ± 0,01), no nisu primijećene značajne razlike među FT-ovima ($p = 0,002$).

Pri usporedbi protisnutih količina natrijeva hipoklorita s različitim načinima rada lasera, ali istim FT-ovima, SSP način općenito je prouzročio značajno manje protiskivanje iriganasa ($p < 0,05$). Skupina G7 (AutoSWEEPS/SWEEPS FT) rezultirala je najvećim protiskivanjem iriganasa (0,54 ± 0,01), a skupina G3 (SSP/PIPS FT) najmanjim (0,26 ± 0,01).

## Rasprava

Klinički uspjeh endodontske irigacije ovisi o postizanju ravnoteže između učinkovitosti i sigurnosti samog postupka, točnije o sprječavanju protiskivanja iriganasa u periapikalna tkiva. LAI je već uspostavljen kao sigurna i učinkovita metoda za aktivacijsku irigaciju. Svrha ovog istraživanja bila je usporediti potencijal protiskivanja iriganasa tijekom različitih metoda LAI-ja na temelju izmjerenih protisnutih vrijednosti, a ne njegovu kliničku relevantnost. U skladu s tim apikalni foramen namjerno je ostavljen otvoren. Ta metodološka postavka rezultat je nedostataka istraživanja koja daju pouzdane vrijednosti periapikalnog tlaka, što je istaknuto i raspravljeno u nastavku teksta.

Rezultati ovog istraživanja pokazali su da se apikalno protiskivanje natrijeva hipoklorita razlikuje među različitim protokolima LAI-ja i FT-ovima; stoga se nulte hipoteze (a) i (b) mogu odbaciti. Istraživanje jasno ilustrira ovisnost između vrste FT-a i laserskoga načina rada. Oblik i veličina FT-ova ključni su u nastanku mjehurića tijekom LAI-ja [28]. Bez obzira na specifični način rada u modalitetu LAI korišten u ovom istraživanju, bilo SSP ili AutoSWEEPS, najniža razina protiskivanja zabilježena je kod PIPS FT-a, a najveća kod SWEEPS safirnoga FT-a. Iako su svi korišteni FT-ovi imali isti promjer, PIPS FT (600/9) razlikuje se zbog svojega stožastog oblika i 5-milimetarskoga vršnog ogoljenja. Ta jedinstvena konstrukcija laserskoga nastavka olakšava stvaranje okruglih kavitacijskih mjehurića koji se pretežno šire lateralno, a ne apikalno, čime se potencijalno smanjuje apikalno protiskivanje iriganasa. Suprotno tomu, postupno stožasti dizajn safirnih SWEEPS-a i ravnih FT-ova ima tendenciju stvaranja izduženih mjehurića za koje je vjerojatnije da će prouzročiti veće apikalno protiskivanje iriganasa [29]. Te razlike u dinamici mjehurića značajno utječu na količinu protisnutog iriganasa jer su izravno povezane s tlakom koji se stvara unutar korijenskog kanala tijekom LAI-ja. Naš cilj nije bio predstaviti rezultate na temelju kojih bi se preporučio određeni protokol, nego pružiti podatke koji mogu poboljšati smjernice za preciznije i uspješnije kliničke protokole LAI-ja u budućnosti.

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Jezeršek et al. [25] found that the AutoSWEEPS mode generated 20–40% higher pressure in the upper two-thirds of the root canal compared to the SSP mode, while both protocols exhibited similar pressure levels in the apical third. In another study, Jezeršek et al. [24] reported that the AutoSWEEPS modality resulted in the lowest irrigant extrusion in simulated root canals compared to SSP and SNI, regardless of the laser energy used. Notably, both LAI modes, AutoSWEEPS and SSP, consistently demonstrated less irrigant extrusion than SNI. Bolhari et al. [23] observed comparable amounts of dye extrusion when using SSP and SWEEPS during photodynamic therapy.

In the present study, the SSP mode showed a lower potential for apical extrusion compared to the AutoSWEEPS mode. Notably, both the SNI and SSP modes (when using radial SWEEPS and PIPS FT) resulted in similar levels of irrigant extrusion (Figure 2).

Even though previous studies have been conducted on artificially created root canals, we strongly believe that root canals of human teeth provided us with more natural, irregular shape which led to more realistic results during such intense fluid dynamics phenomena where small changes may play a significant role. Also, the surface properties of the human root canal model play another significant role in frictional resistance and fluid dynamics compared to the resin models. Furthermore, the access cavities in human teeth serve as a reservoir for irrigants, directly affecting extrusion of irrigant [24, 30, 31] which might be questionable in resin blocks. Although there are no equal root canal morphologies among human teeth, to ensure consistency between samples and minimize variations in root canal anatomy that could influence the study results, maxillary central incisors were selected due to their straight root canals and were standardized by the shape and the foramina size to the achievable level.

Aforementioned factors may be responsible for the discrepancies observed when comparing our results with those of other studies and emphasize the importance of realistic models for a better understanding of irrigant dynamics under clinical conditions [32].

In the study conducted by Vatanpour et al. [31], it was observed that the SSP and AutoSWEEPS modes exhibited less extrusion compared to SNI. On contrary, in Abat et al.'s [33] research on immature extracted teeth, SWEEPS resulted in a greater amount of apical extrusion compared to the NSI method and ultrasonic irrigation. The current research showed similar amounts of extruded irrigant among NSI (0. 05 ml/s IVF) and SSP mode with PIPS and radial SWEEPS FTs, while all other tested groups exhibited statistically significant greater amount of extruded irrigant. As demonstrated, the apical extrusion of an irrigant is influenced by multiple factors, including the periapical pressure (PP), the size and shape of the instrumented root canal (e.g. mature or immature teeth), patency size, canal curvature, irrigation technique, and location of the root apex [25].

Several limitations of this study should be acknowledged. The free volumetric extrusion of NaOCl was measured. As mentioned, methodological protocol was constrained by the lack of accurate PP value. Although the central venous

Jezeršek i suradnici [25] otkrili su da način rada u AutoSWEEPS-u generira od 20 do 40 % viši tlak u gornjim dvjema trećinama korijenskog kanala u usporedbi s načinom rada u SSP-u, dok su oba protokola pokazala slične razine tlaka u apikalnoj trećini. U drugoj studiji ti su istraživači izvijestili [24] da je modalitet AutoSWEEPS-a rezultirao najmanjim protiskivanjem iригansa u simuliranim korijenskim kanalima u usporedbi sa SSP-om i SNI-jem, bez obzira na korištenu lasersku snagu. Značajno je da su oba načina LAI-ja, AutoSWEEPS i SSP, dosljedno pokazivala manje protiskivanje iригansa nego SNI. Bolhari i suradnici [23] primijetili su usporedive količine protisnutoga obojenog iригansa kada su se koristili SSP-om i SWEEPS-om tijekom fotodinamičke terapije.

U ovom istraživanju je način rada u SSP-u pokazao manji potencijal za apikalno protiskivanje u usporedbi s načinom rada AutoSWEEPS. Značajno je da su i konvencionalna irigacija i SSP (kada se koriste radijalni SWEEPS i PIPS FT) rezultirali sličnim razinama protisnutoga iригansa (slika 2.).

Iako su citirana istraživanja provedena na akrilatnim modelima zuba i korijenskih kanala, čvrsto vjerujemo da korijenski kanali humanih zuba daju prirodniji i vjerodostojniji oblik, što je dovelo do realističnijih rezultata tijekom ovako intenzivnih fenomena dinamike iригansa gdje male promjene mogu biti itekako važne. Površinska svojstva korijenskog kanala pravoga zuba također igraju značajnu ulogu u frikcijskoj otpornosti i dinamici fluida u usporedbi s akrilatnim modelima. Nadalje, pristupni kaviteti pravih zuba služe kao spremnik za iriganse i izravno utječu na njegovo protiskivanje [24, 30, 31], što bi moglo biti upitno kod plastičnih blokova. Iako kod ovakvih uzoraka ne postoji jednaka morfologija korijenskih kanala, kako bi se osigurala dosljednost između uzoraka i smanjile varijacije u anatomiji korijenskog kanala koje bi mogle utjecati na rezultate istraživanja, maksilarni središnji sjekutići odabrani su zbog ravnih korijenskih kanala i standardizirani su prema obliku i veličinu foramena na usporedivu razinu.

Ti navedeni čimbenici mogu biti odgovorni za uočene razlike pri usporedbi dobivenih rezultata našeg istraživanja s rezultatima drugih studija i ističu važnost realističnih modela za bolje razumijevanje dinamike irigacije u kliničkim uvjetima [32].

U studiji koju su proveli Vatanpour i suradnici [31] uočeno je da načini SSP i AutoSWEEPS pokazuju manje protiskivanje u usporedbi sa SNI-jem. Suprotno tomu, u istraživanju Abata i suradnika [33] provedenom na zubima s nezavršenim rastom i razvojem korijena, SWEEPS je rezultirao većom količinom apikalno protisnutog iригansa u usporedbi s metodom NSI i ultrazvučnom irigacijom. Naše istraživanje pokazalo je slične količine protisnutog iригansa između NSI (0,05 mL/s IVF-om) i SSP načina rada s PIPS-om i radijalnim SWEEPS FT-ovima, dok su sve ostale testirane skupine pokazale statistički značajno veću količinu protisnutog iригansa. Kao što je rečeno, na apeksno protisnuće iригansa utječe više čimbenika uključujući periapikalni tlak (PP), veličinu i oblik instrumentiranoga korijenskog kanala (npr. završeni i nezavršeni rast korijena), zakrivljenost korijena, tehniku irigacije i mjesto anatomskog foramena zuba [25].

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pressure (5.88 mmHg) could be used instead of the PP, inflammatory altered apical tissue (e.g., granuloma, cyst) and a systemic human disease (cardiovascular disease, valvular abnormalities, cardiac arrhythmias, etc.) may influence a change in the PP [34, 35, 36]. These variabilities underscore the limited clinical relevance of current findings, as precise models of periapical pressure remain elusive.

Furthermore, a review of the literature reveals no data on the volume of extruded irrigant that could potentially lead to NaOCl accidents. However, the present study aimed to demonstrate the difference in irrigant extrusion potential among the same FTs when used in different LAI modes. Therefore, these results provide valuable guidance for the choice of a particular FT during Er: YAG LAI. Our primary aim was not to determine exact clinical extrusion values but to enhance understanding of the likelihood of extrusion during investigated irrigation procedures. While we aspire to generate clinically relevant data in future studies, it is important to acknowledge that current knowledge of periapical pressure is insufficient to construct an accurate model. This limitation persists despite the fact that numerous studies place on the value of periapical pressure as a clear methodological setting.

As shown, the literature review reveals significant discrepancies in the protocols used across studies, resulting in varying levels of irrigant extrusion when comparing SSP and Auto SWEEPS modes. Although the advantages of LAI are well-recognized, the observed variations in irrigation outcomes emphasize the need for further research, which is essential if we want achieve precise and reproducible methodologies that will facilitate more accurate comparisons of results across different studies and clinical settings. This approach will not only improve the reliability of findings but also enhance the overall understanding and application of LAI techniques in clinical practice.

Dakako, treba spomenuti i nekoliko ograničenja ove studije. Mjereno je slobodno volumetrijsko protiskivanje irigansa. Kao što je spomenuto, metodološki protokol bio je ograničen zbog nedostatka egzaktne vrijednosti PP-a. Iako se vrijednost središnjega venskog tlaka (5,88 mmHg) može koristiti umjesto PP-a, upalno promijenjeno apikalno tkivo (npr. granulom, cista) i pojedine sistemske bolesti (kardiovaskularna bolest, valvularne abnormalnosti, srčane aritmije itd.) mogu utjecati na promjenu u PP-u [34, 35, 36]. Te varijabilnosti ističu ograničenu kliničku važnost trenutačno dostupnih znanstvenih spoznaja zato što precizni eksperimentalni modeli ostaju nedorečeni.

Nadalje, pregled literature ne otkriva podatke o volumenu protisnutoga irigansa koji bi mogao završiti hipokloritnim incidentom. Ova je studija imala za cilj pokazati razliku u potencijalu protisnutoga irigansa među istim FT-ovima kada se koriste u različitim načinima LAI-ja. Stoga su ovi rezultati vrijedne smjernice za odabir određenog FT-a tijekom Er:YAG LAI-ja. Naš primarni cilj nije bio odrediti točne kliničke vrijednosti protisnutog irigansa, nego poboljšati razumijevanje o vjerojatnosti protiskivanja tijekom istraženih postupaka irigacije. Iako težimo generiranju klinički relevantnih podataka u budućim studijama, važno je priznati da trenutačno (ne)znanje o preciznoj vrijednosti periapikalnoga tlaka nije dovoljno za postavljanje preciznoga eksperimentalnog modela. Ovo ograničenje i dalje postoji unatoč tomu što autori mnogobrojnih studija pretpostavljaju ovu vrijednost kao jasnu metodološku postavku.

Pregled literature otkriva znatna odstupanja u protokolima koji se koriste u studijama, što rezultira različitim razinama protisnuća irigansa pri usporedbi SSP i Auto SWEEPS načina rada. Iako su prednosti LAI-ja dobro poznate, uočene varijacije u rezultatima ističu potrebu za daljnjim istraživanjima prijeko potrebnima za postizanje preciznih i ponovljivih metodologija koje će omogućiti točnije usporedbe rezultata u različitim studijama i kliničkim okruženjima. Ovaj pristup ne samo da će poboljšati relevantnost, nego će također poboljšati sveukupno razumijevanje i primjenu tehnika LAI-ja u kliničkoj praksi.

## Conclusions

Within the limitations of this study, the AutoSWEEPS mode of Er: YAG LAI resulted in greater extrusion of NaOCl compared to the SSP mode. The use of different FTs had a significant effect on the amount of extruded irrigant: The PIPS FT caused the least extrusion, and the SWEEPS FT caused the highest extrusion of NaOCl, regardless of the LAI modality used.

## Zaključci

Unutar ograničenja ove studije, način rada AutoSWEEPS Er:YAG LAI rezultirao je većim protiskivanjem irigansa u usporedbi sa SSP-om. Korištenje različitih FT-ova imalo je značajan učinak na količinu protisnuća irigansa: PIPS FT izazvao je najmanje protisnuće natrijeva hipoklorita, a SWEEPS FT najveće, bez obzira na primijenjen LAI način rada.

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**Doprinos autora: D. Š.** – nadzor i metodologija; **J. V. H.** – konceptualizacija, pisanje i prikupljanje podataka; **I. B. P.** – metodologija i statistička analiza; **R. D. M.** – nadzor; **I. B.** – projektna administracija i metodologija

**Sažetak**
Svrha ovog istraživanja bila je procijeniti količine apikalno potisnutoga 3-postotnoga natrijeva hipoklorita korištenjem dvaju načina rada lasera Er:YAG (LAI): super kratkoga pulsa (SSP) i fotoakustičnog strujanja emisijom pojačanoga udarnog vala (SWEEPS®) kombinirajući tri vrste laserskih nastavaka (FT) i konvencionalnu irigaciju iglom i štrcaljkom (SNI). **Metode:** Dvadeset izvađenih humanih maksilarnih središnjih sjekutića obrađeno je instrumentima Reciproc® (veličina 40, konus 0,06). Volumetrijski protok iriganta (IVF) standardiziran je korištenjem precizne pumpe s konstantnom isporukom irigansa kroz iglu 27G. Testirani protokoli ispiranja (60 s) bili su: grupa 1: 27-G SNI s 0,05 mL/s konstantnim IVF-om; grupa 2: SSP (10 mJ, 15 Hz, trajanje impulsa 50 µs) + radijalni SWEEPS FT; grupa 3: SSP + fotoakustično strujanje (PIPS) FT; grupa 4: SSP+SWEEPS FT; grupa 5: AutoSWEEPS (20 mJ, 15 Hz, trajanje impulsa 25 µs) + radijalni SWEEPS FT; grupa 6: AutoSWEEPS+PIPS FT; grupa 7: AutoSWEEPS+SWEEPS FT. Svaki protokol ponovljen je 10 puta. Apikalno potisnuti irigans skupljen je i izvagan. **Rezultati:** Značajno manje količine protisnutoga irigansa dobivene su korištenjem SNI-ja i SSP-a s radijalnim SWEEPS-om i PIPS FT-om u usporedbi s drugim testiranim laserskim protokolima ($p < 0,05$). U grupama AutoSWEEPS-a sva tri FT-a imala su slične količine potisnutoga irigansa ($p > 0,05$). **Zaključak:** U ravnim korijenskim kanalima upotreba različitih laserskih nastavaka u načinu rada korištenjem AutoSWEEPS-a pokazala je veći potencijal za protiskivanje iriganse.

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**MeSH pojmovi:** obrada korijenskog kanala; liječenje laserom; sredstva za ispiranje korijenskog kanala
**Autorske ključne riječi:** Er:YAG, laserski aktivirana irigacija; fotoakustično strujanje izazvano fotonima; korijenski kanal; natrijev hipoklorit; fotoakustično strujanje emisijom pojačanoga udarnog vala

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