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Laser Disinfection Acts as Biofilm-Disrupter in Periprosthetic Joint Infection (PJI)

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ABSTRACT

Infections after joint arthroplasties represent a devastating and progressively escalating complication with increased morbidity and mortality. The eradication of biofilms from infected implants is still an unsolved challenge. The erbium-doped yttrium aluminum garnet (Er:YAG) laser, which delivers high-energy light for rapid tissue ablation, may offer an advancement. This study aimed to evaluate the effectiveness of this laser in removing biofilms from infected implant surfaces. In this prospective study, 31 patients with 33 early postoperative or acute hematogenous periprosthetic joint infections (PJIs) were treated with our modified procedure of debridement, antibiotics, laser irradiation and implant retention (DALIR). Biofilm removal was compared between mechanical cleansing alone and the additional use of Er:YAG laser light. Therefore, swab cultures from the implants were taken at three distinct occasions: post-arthrotomy, after mechanical cleansing with a fluid disinfectant (LavaSurge), and after additional Er:YAG laser irradiation. The success rate of the DALIR procedure was compared with a prior group ($n = 34$) that underwent DAIR procedures without the Er:YAG laser at our clinic. The implementation of the laser system in our DAIR procedure was uncomplicated. The additional Er:YAG laser therapy significantly reduced viable microorganisms on implant surfaces (9.1%) compared to mechanical cleaning alone (42.4%; $p < 0.01$). The healing rate in our cohort was 78.1%, a substantial improvement over the previous rate of 44.1% ($p < 0.01$). Therefore, we recommend the use of Er:YAG laser irradiation as an additional tool for surface disinfection of metal implants in PJIs whenever a DAIR procedure seems to be beneficial.

Trial Registration: ClinicalTrials.gov identifier: NCT06440564.

Level of Evidence: 2B.

1 | Introduction

1.1 | Background

Total joint arthroplasty (TJA) continues to be one of the most successful surgical interventions in medicine [1]. In the Organisation for Economic Co-operation and Development countries, a total of 1.69 million hip and 1.53 million knee endoprostheses were implanted 2015 [2]. Unfortunately, approximately 1%–2% of all TJA patients develop a periprosthetic joint infection (PJI) following surgery [3–5]. Although more common during the early years after TJA, PJI can present anytime during the lifetime of the patient. PJIs occur less frequently than aseptic failures and dislocation, but infections represent a devastating complication with severe health and socioeconomic implications that is associated with increased

morbidity and mortality [6]. The 5-year overall survival of 67% for PJI after total hip arthroplasty (THA) and 72% after total knee arthroplasty (TKA) are comparable to those for common cancers (bone and joint, cervix, leukemia) and even poorer than other malignancies (bladder, anus, Hodgkin/non-Hodgkin lymphoma, uterine, thyroid, melanoma, breast, prostate, kidney, and renal pelvis) among US adults [7, 8].

Despite widespread adoption of antimicrobial precautions such as laminar airflow, antibiotic prophylaxis, and iodine-impregnated surgical adhesive wraps, the risk of PJI does not appear to have changed over time. The incidence of PJI in the future is anticipated to scale up proportionately with the demand for arthroplasties, which is projected to increase substantially in the coming decade [6].

Implant-related infections are predominantly caused by microorganisms that form biofilms [9–11]. Within biofilms, microorganisms are enclosed in a polymeric matrix and develop into complex communities, resembling multicellular organisms [12]. The biofilm shields the bacteria from host immune responses and from antimicrobial agents or antibiotics. Reports in the literature indicate that 500–5000 times higher levels of antibiotics are needed to achieve the same antimicrobial effects on biofilm bacteria than are needed for planktonic bacteria [13–15].

The eradication of biofilms from infected implants is still an unsolved and intensely investigated challenge [5, 16–20]. Until now, no generally approved treatment concept for implant-related infections could be established, but for early postoperative (< 6 weeks) and acute hematogenous (duration of the symptoms < 3 weeks) infections debridement, antibiotics, and implant retention (DAIR) procedures are generally recommended [21].

The advantage of a DAIR procedure lies in its ability to reduce the morbidity associated with complete implant removal and to avoid a second-stage surgery. This approach eliminates the need for a prolonged debilitating interval period or spacer-related complications, minimizes post-operative stiffness and arthrofibrosis, and spares patients the risks of two major operations, which are often associated with poorer functional outcomes.

1.2 | Rationale

A relatively new concept for the treatment of microbial infections has been developed by dental surgeons, who use laser irradiation to remove infected tissue and biofilms from teeth and implants in the case of periodontitis and peri-implantitis. These procedures look quite promising and can be converted to traumatologic and orthopedic settings [22]. The Er:YAG laser emits infrared light at a wavelength of 2.94 μm, which corresponds to the absorption maximum of water. Due to the high absorption of this wavelength in water, the irradiant energy of the laser pulse evaporates a relatively small tissue volume, which leads to microexplosions and an effective superficial tissue ablation (~60 μm/pulse) with minimal thermal damage (< 10 μm/pulse) [23]. The Er:YAG laser is already widely used for surgical incision/excision, cutting ablation, vaporization, and coagulation of soft and hard tissue. Orthopedic surgeons could also profit from advancements in laser technology, particularly as a means of biofilm disruption in PJIs. A precursor study on Schanz pins from removed external fixators and other metal components showed that this laser effectively disinfects implants, eradicating pathogens without damaging the implant or causing microbial resistance. This study compares the effectiveness of laser treatment versus standard mechanical cleaning with a liquid disinfectant in removing biofilms from PJI implants, based on microbiological analysis of swab cultures.

The aims of this study were to (1) evaluate if the Er:YAG laser disinfection of metal implants can be integrated in a DAIR procedure; (2) assess whether the incorporation of laser disinfection offers an advantage over established disinfection methods; (3) to assess how reliable swab cultures are compared to other microbiological tests (synovial fluid, implant sonication, tissue samples, PCR); and (4) to determine the impact of laser irradiation on healing rates in DAIR procedures.

The perspective of having one more arrow in the quiver in a DAIR procedure, where prosthetic components fixed to the bone are retained, would be extremely desirable.

2 | Methods

2.1 | Study Design and Setting

We conducted a single-institution, prospective interventional comparative study at a primary urban care center.

2.2 | Participants

Thirty-one patients with 33 PJIs who had been treated with a DIAR procedure between 2021 and 2024 at the University Clinic of Orthopedics and Trauma Surgery (Paracelsus Medical University Salzburg, Austria) were enrolled into this prospective study. PJI was defined according to the European Bone and Joint Infection Society (EBJIS) criteria [24]. Patient-related and surgery-related parameters were registered, including age, ASA score, body mass index (BMI), previous joint operations, and type of microorganism involved (Table 1).

According to the system proposed by Osmon et al. and Toms et al., early postoperative (≤ 6 weeks) and acute hematogenous (acute onset in a well-functioning prosthesis, secondary to hematogenous spread, symptoms ≤ 4 weeks) PJIs were treated with a DIAR procedure [25, 26]. The procedure included a radical synovectomy with removal of all infected or necrotic tissue, acquiring multiple tissue samples, extensive irrigation, Er:YAG Laser irradiation of the implant surface (as a biofilm disrupter), and the exchange of modular components. The method was therefore renamed to “Debridement, Antibiotics, Laser irradiation and Implant Retention (DALIR)”.

All procedures were performed by revision surgeons in a laminar airflow-fitted operating room. All patients underwent an Infectious Disease (ID) consult during hospitalization. The DALIR procedure was generally followed by a 2-week course of intravenous antibiotic therapy (according to the antibiogram) and at least another 6-week course of oral antibiotic therapy afterwards.

TABLE 1 | Patients' descriptive data.

	DALIR	DAIR
Number of patients	31	33
Number of PJIs	33	34
Age (years)	73 (±12.6)	71.9 (±10.9)
Sex (m/f)	17 (m) 14 (f)	20 (m) 13 (f)
ASA Score	2.6 (±0.6)	2.7 (±0.5)
BMI	29 (±7.5)	29.5 (±6)
Type of arthroplasty (TKR, THR, TSR)	19 (TKR)	17 (TKR)
	10 (THR)	16 (THR)
	4 (TSR)	1 (TSR)
Duration of symptoms (weeks)	2.6 (±1.4)	2.3 (±1.2)
Type of infection	17 (early postop.)	17 (early postop.)
	16 (acute haemat.)	17 (acute haemat.)
Interval arthroplasty - DALIR (days)	1485 (±2312)	898 (±1591)
	29.5 (±16.1) early postop.	27.8 (±13.5) early postop.
	2958 (±2611) acute haemat.	1768 (±1774) acute haemat.
Previous joint operations besides index arthroplasty	22/33 (66.7%)	21/34 (61.2%)
Previous joint operations due to infection	14/33 (42.4%)	10/34 (29.4%)

Note: The DAIR control group was not prospectively investigated but rather analyzed retrospectively.
Abbreviations: ASA Score = American Society of Anesthesiologists Score, BMI = body mass index, THR = total hip replacement, TKR = total knee replacement, TSA = total shoulder replacement.

2.3 | Patients' Descriptive Data

This study included two patient groups: a prospective intervention group treated with the DALIR procedure and a retrospective control group treated with conventional DAIR. The DALIR group consisted of 31 patients with 33 PJIs, while the DAIR group included 33 patients with 34 PJIs. The mean age in the DALIR group was 73 years (range: 45–91) and 71.9 years (range: 53–92) in the DAIR group. The average body mass index (BMI) was 29 ± 7.5 kg/m² (range: 20–49) and 29.5 ± 6 kg/m² (range: 21–46), respectively. The mean ASA score was similar between groups: 2.6 ± 0.6 for DALIR and 2.7 ± 0.5 for DAIR. In the DALIR group, 22 joints (66.7%) had undergone prior surgical procedures in addition to the index arthroplasty, compared to 21 joints (61.2%) in the DAIR group. Previous infection-related interventions were documented in 14 cases (42.4%) in the DALIR group and 10 cases (29.4%) in the DAIR group. The types of arthroplasty treated were similarly distributed: 19 total knee replacements (TKR), 10 total hip replacements (THR), and 4 total shoulder replacements (TSR) in the DALIR group, versus 17 TKR, 16 THR, and 1 TSR in the DAIR group. In both groups, infections were classified as early postoperative (DALIR: 17 cases, 51.5%; DAIR: 17 cases, 50.0%) or acute hematogenous (DALIR: 16 cases, 48.5%; DAIR: 17 cases, 50.0%). The mean duration of symptoms before treatment was 2.6 ± 1.4 weeks in the DALIR group and 2.3 ± 1.2 weeks in the DAIR group. The interval between the index arthroplasty and the infection-related revision procedure averaged 1485 ± 2312 days in the DALIR group and 898 ± 1591 days in the DAIR group. For early postoperative infections, the respective means were 29.5 ± 16.1 days (DALIR) and 27.8 ± 13.5 days (DAIR); for acute hematogenous infections, 2958 ± 2611 days (DALIR) and 1768 ± 1774 days (DAIR) (Table 1).

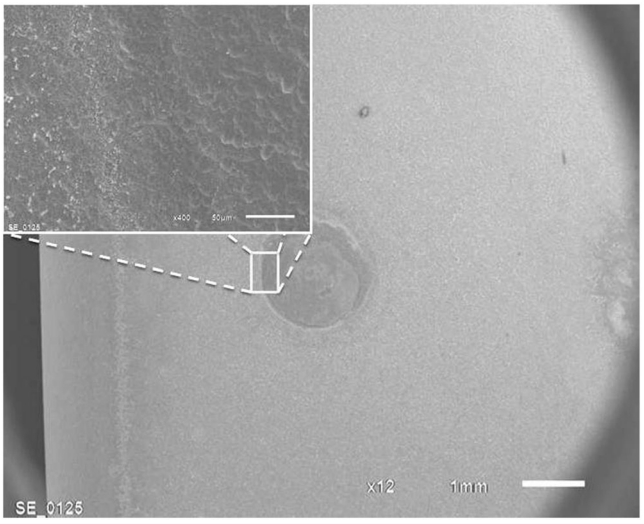

FIGURE 1 | Scanning electron micrographs of a cultivated metal plate after a single Er:YAG laser impulse show the discernible laser spot. Higher magnification reveals the complete removal of biofilm with 2 J.

2.4 | Description of Experiment

For laser irradiation, we used a Burane XL Er:YAG laser (Alma Lasers GmbH, Germany) with a maximum energy of 2500 mJ and a maximum power of 30 W. The laser beam was used in the slightly defocused mode (spot size 4–5 mm diameter), applying 2500 mJ at a frequency of 20 Hz. The fluence of the ablative pulses was 13–20 J/cm². These parameters are the result of our preliminary findings that showed a complete biofilm removal with a single-laser exposure (Figure 1), no effect on the implant

surface, and the well-known predictable ability of tissue removal of about 2.5 μm/pulse/J/cm^2 and the collateral thermal tissue damage of about 20 μm [22, 23, 27, 28]. Only cobalt-chromium (CoCr) arthroplasty components were treated with the Er:YAG laser, as the application of focused thermal energy could potentially induce cracking of an Oxinium (oxidized zirconium) surface.

A noncontact IR Thermometer (Bosotherm, BOSCH+SOHN GmbH u. Co. KG, Germany) was used to measure the heating of the implant surface during Er:YAG laser irradiation.

For irrigation, we used 5–8 L of sterile Ringer's solution and 1 L of LavaSurge (0.04% Polihexanid, B. Braun Austria GmbH) with a pulse lavage system (Pulsavac Plus Wound Debridement System, Zimmer Biomet, Switzerland).

The removed implant components (femoral heads, liners, inserts) were placed in sterile plastic containers and Ringer's solution was added before the containers were subjected to sonication according to the method described by Trampuz et al. [29]. We used a Bacto-Sonic Biofilm-sonication bath (Bandelin Electronic GmbH & Co. KG, Germany) with 35 kHz for 1 min and an Eppendorf Centrifuge 5810R (Eppendorf AG, Germany) at 4000 rpm for 5 min.

Additionally, we collected swab cultures from the surfaces of each implant component that was fixed to the bones at three different stages of the DALIR procedure: post-arthrotomy (baseline), after mechanical cleansing and irrigation with LavaSurge (Intervention 1), and after Er:YAG laser irradiation (Intervention 2). In this way, at least six swabs were collected per patient. Even if a pathogen was detected in only one of the two joint components, the swabs of this series were classified as positive.

2.5 | Primary and Secondary Study Outcomes

The primary outcome was the comparison of biofilm removal from the implant surface with mechanical cleansing alone (LavaSurge administered with Pulsavac) and the additional use of Er:YAG laser light.

The secondary outcome was the "healing rate," defined as eradication of infection at a minimum of one year following the DALIR procedure. Procedural success was determined by the absence of antibiotic therapy, lack of clinical signs of infection, and no requirement for subsequent infection-related surgical interventions.

2.6 | Ethical Approval

This prospective study was approved by the local ethics committee (Salzburg, Austria, 1087/2021) and adhered to the Declaration of Helsinki. All patients provided written informed consent.

2.7 | Statistical Analysis

Results are expressed as percentages to enable comparisons across groups. Statistical significance was assessed using McNemar's tests, Chi-square tests, *T*-tests, and two-proportion *Z*-tests. p values < 0.05 were considered statistically significant. All calculations were carried out using GraphPad Prism 9.5.1 software.

One patient died from unrelated causes during the study before the minimum follow-up and was excluded from the final analysis.

3 | Results

3.1 | Integration of an Er:YAG Laser in a DAIR Procedure

The presented DALIR procedure differs in so far from a standard treatment that after exposure all accessible metal implant surfaces and the adjacent soft tissue are irradiated manually with the Er:YAG laser all over line-by-line with an intended overlap of approximately 10% at constant spot diameter (Figure 2). The use of laser treatment resulted in a mean increase in operative time of 13.1 minutes compared to the control group, which conveniently coincides with the necessary exposure time for most antiseptic irrigation solutions [30]. However, this difference did not reach statistical significance ($p = 0.17$). The setup time for the laser system—including activation and sterile draping—is comparable to the preparation required for standard intraoperative imaging equipment, such as an X-ray machine. A supplemental video is provided to illustrate the startup procedure of the laser system. The implementation of the laser device in the OR setting was therefore uncomplicated (Figure 3).

3.2 | Advantages of Additional Laser Disinfection Compared to Established Disinfection Methods

Microbes were considerably reduced after both mechanical cleansing with LavaSurge alone and after additional laser irradiation. The prevalence of viable microorganisms obtained from implant surfaces through swab cultures was highly significantly ($p < 0.001$) diminished after additional Er:YAG laser therapy (9.1%) in comparison to only mechanical cleaning with LavaSurge (42.4%) (Figure 4).

3.3 | Reliability Assessment of Swab Cultures Compared to Other Microbiological Tests (Synovial Fluid, Implant Sonication, Tissue Samples, PCR)

Serological investigations showed considerably elevated levels of C-reactive protein (CRP) (median 13.5 mg/dL) alongside with almost normal white blood cell counts (median 9.9 G/L).

Joint aspiration detected a highly elevated leukocyte count of 102,670 (±90,112) cells/μL, on average. Polymerase chain reaction (PCR) of the synovial fluid was positive in 90.3% of our cases and detected the same microorganism as implant sonication in 70.9%. The sensitivity of PCR performed on sonication fluid was 64.5%, and it demonstrated a concordance rate of 74,2% when compared to the results of sonication cultures.

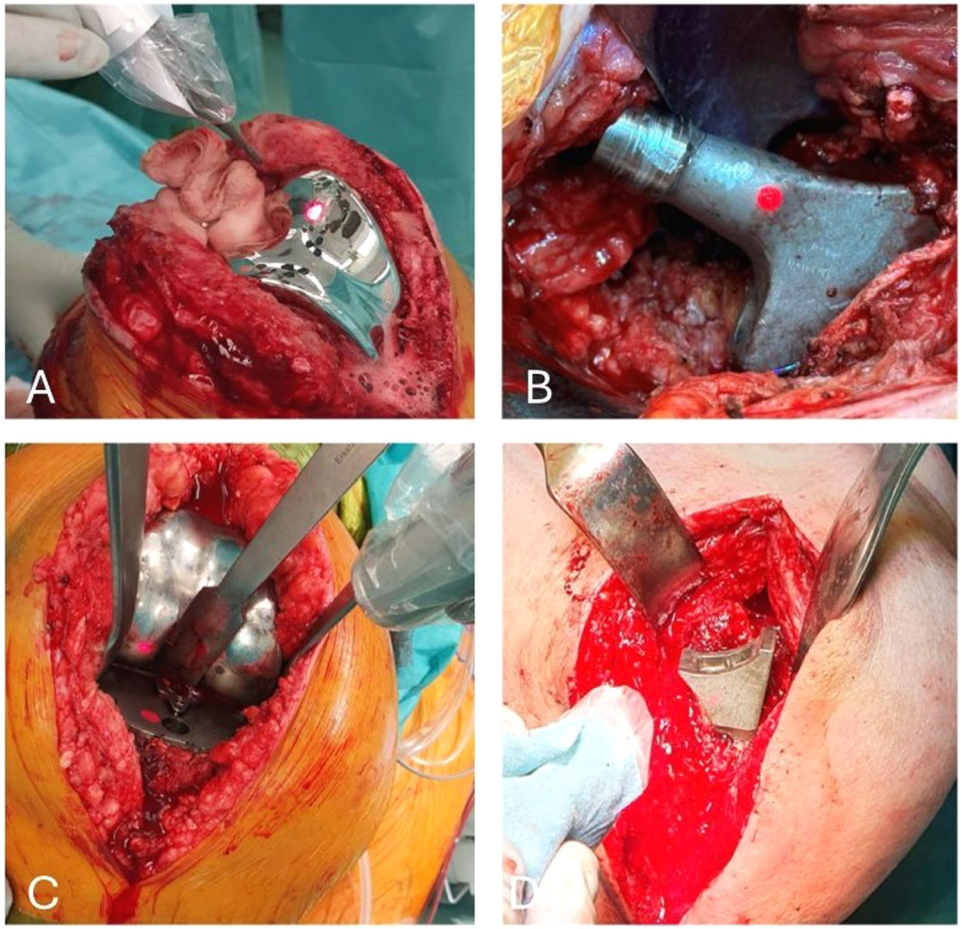

FIGURE 2 | Biofilm disruption with the Er:YAG laser during a DALIR procedure. The red spot serves as the guiding beam for the otherwise invisible infrared Er:YAG laser beam. (A, C) Treatment of a TKR with femoral (A) and tibial (C) exposure and component irradiation. (B) Laser disinfection of the exposed femoral shaft in an infected THR. (D) Exposure and irradiation of a reverse total shoulder arthroplasty (RSA).

The most commonly isolated organism was *Staphylococcus aureus* (39%), followed by *Cutibacterium acnes* (18%), *Staphylococcus epidermidis* (18%), *Pseudomonas aeruginosa* (9%), and *Escherichia coli* (9%). Identical pathogens in all microbiological samples were detected in 66.7% of our PJI cases. Figure 5 presents a comparison of the positive percentage agreement (PPA) among the various microbiological tests. Swab cultures detected pathogens in all but one sample (96.9%). Remarkably, the highest rates of consistent outcomes (84.8%) were detected between synovial fluid and swab cultures from the implant surface as well as between synovial fluid and tissue samples (81.8%). With 75.7%, the PPA of implant sonication and swab cultures was equally high as for tissue samples and swab cultures and higher than for synovial fluid and sonication (72.7%).

Histological analysis of intraoperative tissue samples detected the presence of acute inflammation in 66.6%, chronic inflammation in 29.6%, and no inflammation in 3.7% of our cases according to a classification proposed by Morawietz et al. [31].

3.4 | Impact of Laser Irradiation on the Healing Rates of DAIR Procedures

In our mixed patient cohort, we were able to achieve a healing rate of 78.1% ($n = 25$). Due to a high risk of reoccurrence of PJI, three patients were treated with a prolonged antibiotic suppression therapy following the DALIR procedure. Although there were no signs of infection at the final follow-up, the overall success of the operation remained uncertain, leading to the classification as "not healed." One patient underwent a second DAIR procedure, two a resection arthroplasty of the hip, and two a two-stage revision TKR. On average, these patients had to undergo 3.6 additional operations.

The success rate of the DALIR procedure was compared to a control group comprising 33 patients (34 joints) who underwent DAIR procedures between 2019 and 2023 at our clinic, before the implementation of the Er:YAG laser. These DAIR procedures were performed by the same surgeons, with no procedural modifications other than the incorporation of the laser system. In contrast to the DALIR group, the control group was not prospectively investigated but rather analyzed retrospectively. No statistically significant differences were observed in the demographic and clinical characteristics (age, gender, BMI, symptom duration, and history of previous surgeries) between the two groups (Table 1). The overall success rate was 44.1% in the control group compared to 78.1% in the DALIR group ($p = 0.008$) (Figure 6).

In both groups, early postoperative infections demonstrated higher healing rates compared to acute hematogenous infections. Specifically, the healing rate for early postoperative infections

was 47.1% in the DAIR group, whereas it was significantly higher in the DALIR group at 93.7% ($p = 0.003$). In contrast, the healing rates for acute hematogenous infections were 41.2% in the DAIR group and 50% in the DALIR group, with this difference not reaching statistical significance ($p = 0.6$).

FIGURE 3 | Setup in the operating theater with the Er:YAG Laser in front. The laser beam is delivered with an articulated arm and a handpiece.

Due to the temperature increase caused by laser irradiation, implant components were measured with an infrared thermometer immediately following the irradiation process. The highest temperature increase measured was +4.5°C (from 21.5°C to 25°C). No special cooling devices (air or air-water spray) were used, but the operating field was occasionally flushed.

4 | Discussion

A DAIR procedure for PJIs should never be mistaken with a quick operation or a simple washout of a joint, since the use of antimicrobial agents or antibiotics alone does not provide an effective countermeasure particularly over the long term [32–34]. The word "procedure" defines itself as a series of actions conducted in a certain order or manner. The surgical steps may differ a from clinic to clinic but always include the acquisition of multiple tissue samples, a radical debridement of all infected tissue, the exchange of all modular components, an extensive irrigation and mechanical cleansing of the implant and sometimes a local antibiotic [4].

In this study, we tested a modification of the standard DAIR technique for infected arthroplasties with respect to the use of Er:YAG laser light as a biofilm disrupter (DALIR). The destructive effect of the Er:YAG laser derives from the spontaneous heating and evaporation of water that is part of every organism. Therefore, this laser has already found application in dentistry, wherein clinical and experimental studies have substantiated the benefits of laser irradiation for decontamination of implant surfaces [35].

In a precursor study on removed Schanz pins from external fixators this laser has proven its high potential for implant disinfection since the laser light offers a precise, secure, complete, and nontoxic eradication of all kinds of pathogens from metal implants without damaging the implant and without the possible development of resistance of microbes [22]. Now, the

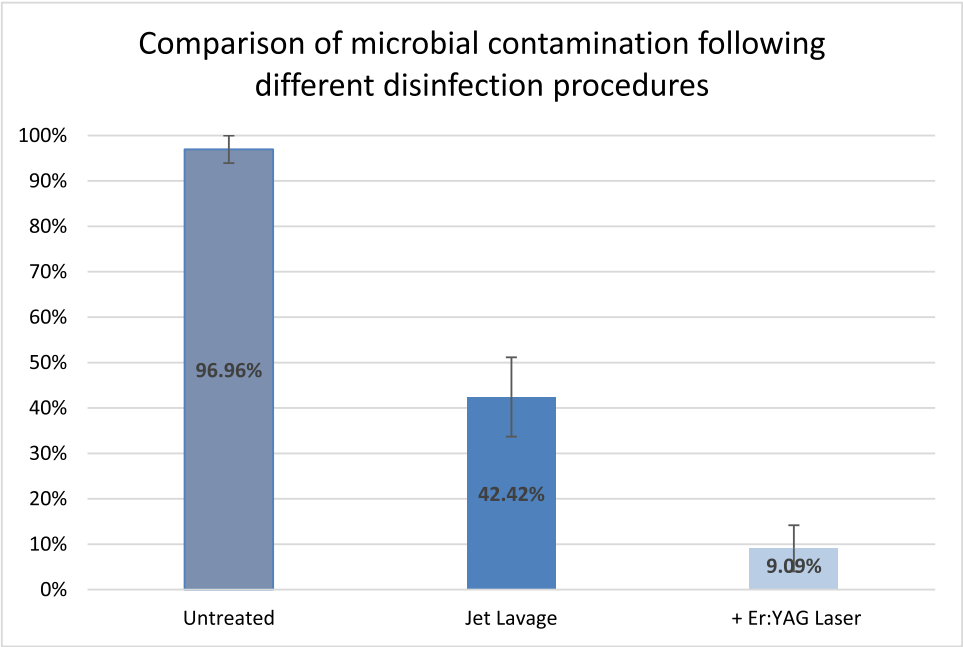

FIGURE 4 | Detectable microbes via swab culture were significantly less frequent in implants additionally treated with Er:YAG laser (9.1%) compared to those that were solely mechanically cleaned (42.4%; $p < 0.001$) and the control group (96.9%; $p < 0.0001$).

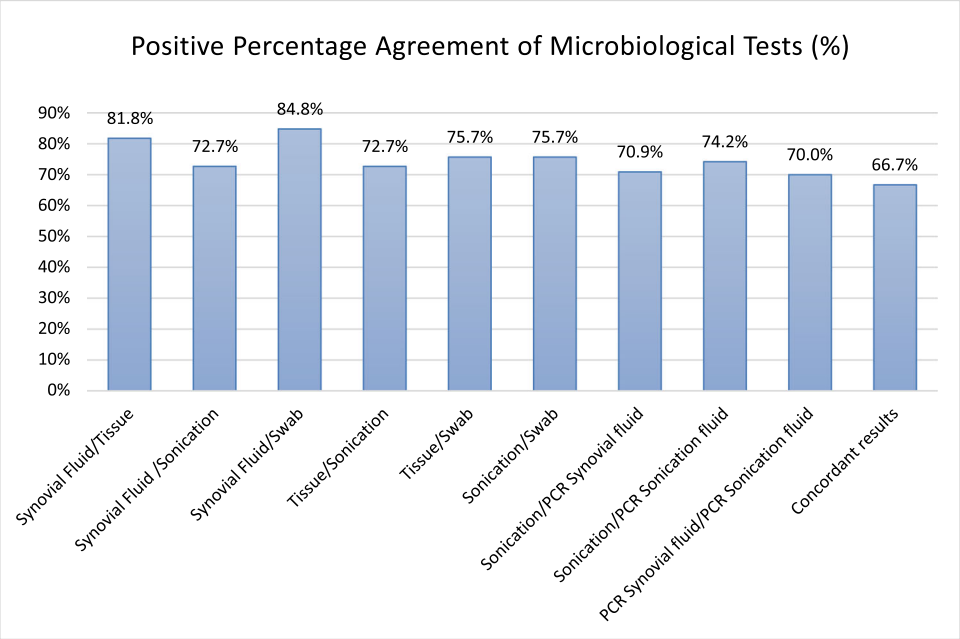

FIGURE 5 | Comparison of sensitivity (positive percent agreement) for microbiological tests. PCR = polymerase chain reaction.

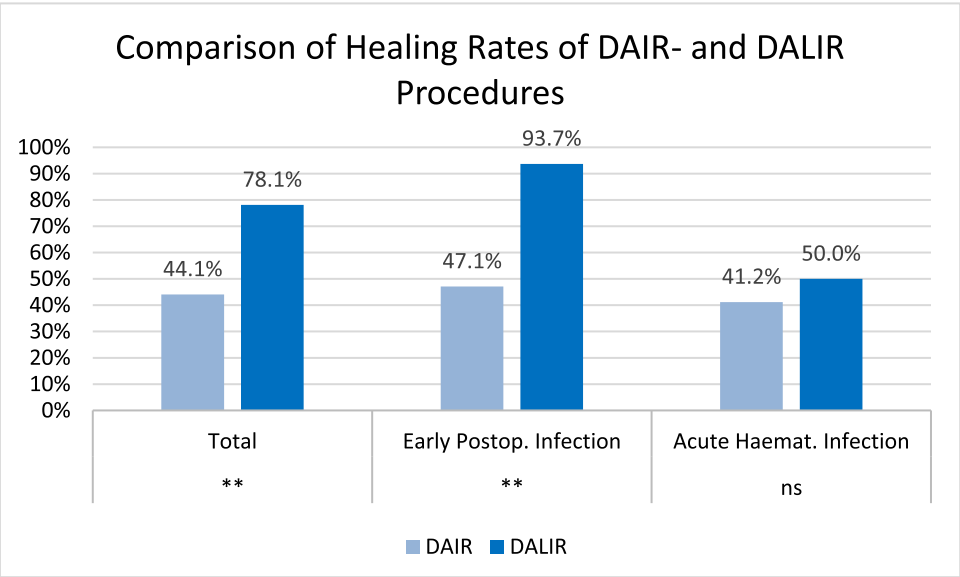

FIGURE 6 | Comparison of healing rates of DAIR- and DALIR procedures. The column chart showing the effect of the implementation of laser treatment in PJI cases in our clinic. ** indicates $p < 0.01$. Differences marked with ns are not statistically significant.

removal of bacteria and fungi from PJI implants was microbiologically analyzed using swab cultures and compared with the state-of-the-art treatment of mechanical cleaning with a liquid disinfectant.

4.1 | Limitations

There are several limitations of our study, including a small sample size, which makes it arguable to draw reliable conclusions from the data. In addition, both the swab cultures and the hand-held laser beam allow for the possibility of inaccuracies. Repeated swabbing of the same area may also compromise the accuracy and interpretability of culture results. Furthermore, we compared our healing rate with a control group that was retrospectively assembled from patients treated within a similar timeframe and under identical clinical indications, though not prospectively enrolled in the study. The comparison of healing rates with data from the international literature inherently presents challenges regarding the validity of direct comparisons due to potential differences in study methodologies, patient populations, and treatment protocols. Moreover, we cannot report long-term clinical outcomes and further investigation is mandatory. These limitations should be taken into consideration when interpreting the results of the study.

The strength of this study design was that we could directly measure the effect of additional laser irrigation during the same operation on the same patient and the same implant. Furthermore, the application of the Er:YAG laser represented the only modification compared to the control group.

4.2 | Integration of an Er:YAG Laser in a DAIR Procedure

Laser irradiation during such operations can be completed with relatively little time expenditure (~10 s/cm^2). Meanwhile, the remaining wound and implant should be covered with a saturated compress to achieve optimal exposure time and cleansing results of the fluid disinfectant. It is important to use a disinfectant that is not highly flammable, avoiding options like high-concentration alcohol.

The implementation of an Er:YAG laser in a trauma care or orthopedic unit and the training are feasible. The acquisition costs of about 35,000 Euro are justified and match the hospital expenses for a single two-stage procedure in PJI treatment [36, 37].

Possible clinical application areas for the Er:YAG laser irradiation besides early and acute prosthetic joint infections are osteosynthesis-associated infections that are treated with a debridement and retention concept.

4.3 | Advantages of Additional Laser Disinfection Compared to Established Disinfection Methods

The hypothesis was that the combination with the additional technique of laser irradiation would lead to a more complete biofilm removal and thereby an increase in the overall success rate in implant-retention revision surgery.

This study demonstrates that Er:YAG laser light significantly enhances biofilm eradication on metal implants in PJI cases. A direct comparison of swab cultures taken from the surfaces of identical implants showed that laser irradiation reduced viable microbes to 9.1%, while brushes and pulsed irrigation alone left 42.4% of samples with viable microbes, a significantly higher proportion ($p < 0.001$). This finding is consistent with the results of our preliminary study, which evaluated the efficacy of biofilm removal from metal implants using a liquid disinfection versus the Er:YAG laser. Similar conclusions have been reported in other preclinical studies [22, 33, 34].

When the high-energy beam of an Er:YAG laser strikes a water-containing surface, it causes rapid heating and explosive ablation of any tissue. A resistance of certain bacterial strains is therefore physically implausible. We hypothesize that the freehand application of the laser may have led to irregularities

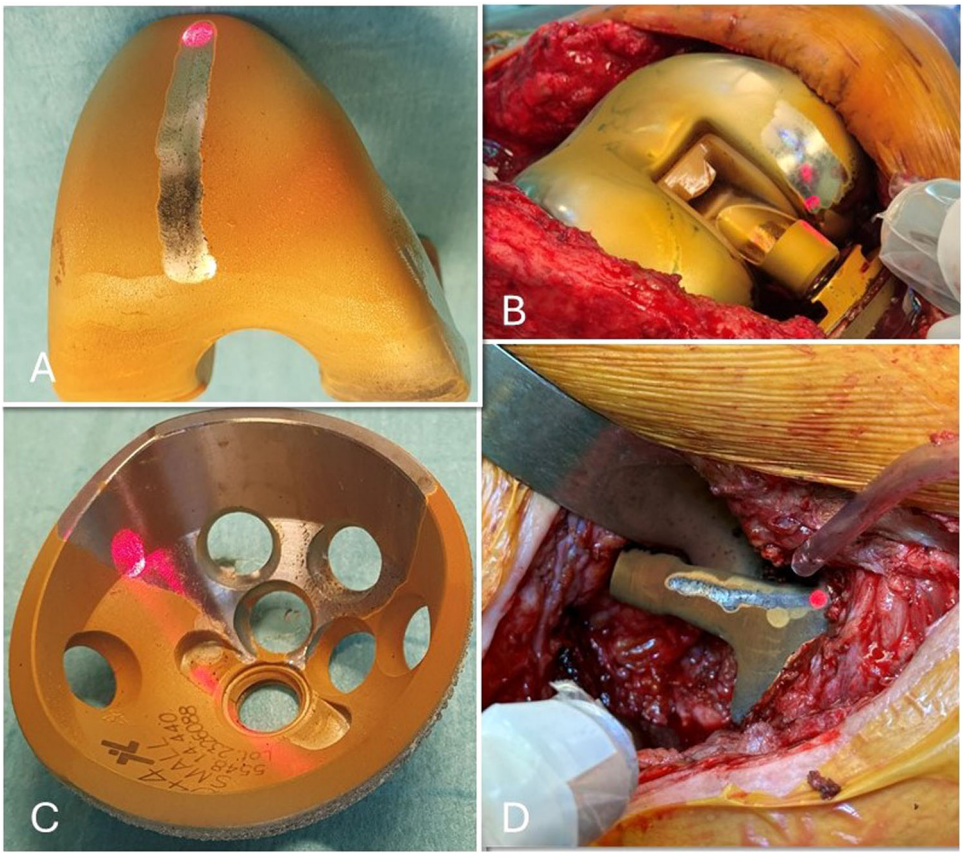

FIGURE 7 | Although staining the implant surface with Povidone Iodine spray was not part of the study protocol, it proved useful in distinguishing between areas that had been treated with the laser and those that had not. Trials with the femoral component (A) of an explanted TKA, as well as an acetabular cup (C), demonstrate a distinct color difference between irrigated a not-irrigated areas of the implants. This observation also holds true for the exposed and partially irrigated femoral component (B) and shaft (D) during the DALIR procedure.

and uneven irradiation of the implant surface, potentially facilitating the detection of microbes even after laser treatment in three of our samples. A feasible countermeasure could be coloring the surface of the prosthesis with Povidone Iodine spray (Figure 7).

4.4 | Reliability Assessment of Swab Cultures Compared to Other Microbiological Tests (Synovial Fluid, Implant Sonication, Tissue Samples, PCR)

The spectrum of microbes forming biofilms on PJIs was analyzed using synovial fluid, implant sonication, tissue samples, swab cultures from the remaining implants, and PCR tests. As expected, *S. aureus* was the most common pathogen associated with PJI in both of our groups. The advantages of sonication are widely accepted, especially in patients who had received antimicrobial therapy within 14 days before surgery [29, 38, 39]. While swab cultures are generally discouraged in the diagnosis of joint infections, our study found that they identified pathogens in all but one sample. Swabs identified the same pathogens as implant sonication in 75.7% of cases and matched the pathogens found in synovial fluid in 84.8% of samples. In this study, the joints were fully exposed, ensuring that contamination of the swab samples from the skin and surrounding tissue was excluded. Therefore, swab cultures can serve as an effective self-check for the sterilization process of infected implants established at the own clinic.

We observed that the utilization of PCR from joint aspiration fluid exhibits greater accuracy compared to that from sonication fluid. The sensitivity achieved aligns with findings from other studies [40].

4.5 | Impact of Laser Irradiation on the Healing Rates of DAIR Procedures

The achieved healing rate of 78.1% was considered satisfactory and placed within the upper quantile of comparable studies. For our own patient collective, the implementation of the Er:YAG laser led to a significantly higher healing rate when compared to our standard DAIR procedure (44.1%). The most notable effect was the significant improvement in the healing rate of early postoperative infections. The cause of the significantly poorer healing rates in acute hematogenous infections cannot be reliably determined. Given the small number of patients, the three individuals who also received long-term antibiotic suppression therapy could account for a statistical difference. Another possible explanation is that these patients may have had a smoldering infection for some time, which only became symptomatic at a later stage.

The success rate of a DAIR procedure varies significantly in literature (31-80%) with a high degree of methodological variation and is strongly dependent on patient selection. Timing seems to be the crucial factor, and good results can be expected in the case of an early postoperative or acute hematogenous infection [4, 41].

Osmon et al. noticed that DAIR procedures may be used in patients who do not meet these criteria, but state that worse results can then be expected [26]. Success rates between 28% and 62% have been reported in review articles when DAIR is applied to chronic infections, as compared between 31% and 100% for acute infections [41, 42].

Several factors have been associated with treatment failure: longer duration of symptoms, a longer time after initial arthroplasty, the need for more debridement procedures, the retention of exchangeable components, infections caused by *Staphylococcus*, MRSA, or *Pseudomonas aeruginosa* species, patient's own immune deficiency, a high ASA score, poor local tissues viability, and the presence of rheumatic disease [4, 9, 41]. However, patients with comorbidities and a high intraoperative risk profit most from a successful DAIR procedure. These patients are often not eligible for a two-stage procedure with its unique requirements, including the lack of mobilization over weeks in case of problematic stable joints. Therefore, DAIR is often employed as a pragmatic treatment option, even in suboptimal clinical scenarios where ideal conditions for success are not met [26, 41].

Finally, it remains an individual decision if a DAIR procedure seems beneficial for a patient even if the preconditions are not optimal. Even more important is the creation of ideal conditions during the surgical procedure. The residue-free biofilm removal is mandatory when an infected implant is treated, since even a few remaining living cells can cause recurrent infections with antibiotic resistance and immune evasion [32].

During the laser irradiation of the implants, we measured a maximum temperature increase of 4.5°C. However, heat is a double-edged sword that has a distinct bactericidal or bacteriostatic effect but may also harm the surrounding tissue. If a laser is used in a clinical setting, some thermal damage to the surrounding tissues cannot be avoided (direct irradiation, reflection, and heating of the implant). In this study, the heating of the implants during laser irradiation was minimal and far-away from temperatures critical for bone necrosis (50°C for 1 min) [43]. Therefore, adverse effects on bone metabolism due to Er:YAG laser treatment are excluded. In our setting, the temperature upshift of the implant was also not high (48°C) or long (10 min) enough to affect growth kinetics of the bacterial strains negatively [44]. A thermal damage to bacterial biofilms in regions of the implant that are not directly accessible for the laser light (bone-implant interface) cannot be expected. Laser effects occur only on optically accessible sections of the implant. In areas that are difficult to access—such as the posterior condyles of knee prostheses—laser light may be reflected when targeting the tibial surface; however, such reflections are inherently more difficult to control. The effect of noncontact induction heating on metal implants is currently investigated in ex vivo and animal models and could also play a role during DAIR procedures in the future [19].

This study demonstrated that the Er:YAG laser effectively removes biofilms from metal implants without harming the patient or the implant. The method is effective against any pathogens, which is crucial given the rising resistance of microbes to pharmaceuticals and chemicals. The Er:YAG laser offers a distinct advantage over fluid disinfectants by enabling

not only the destruction of biofilms on metal implants but also the precise, noncontact removal of infected soft and hard tissues, thereby promoting the formation of a sterile wound surface. When used in conjunction with a fluid disinfectant capable of penetrating areas inaccessible to the laser, incorporating the Er:YAG laser into a DAIR procedure is advantageous due to its ability to accurately eliminate biofilms without additional tissue damage or promotion of microbial resistance.

4.6 | Conclusion

The treatment of PJIs, just like its diagnosis, requires a multimodal approach. Success has many fathers, but it is undisputed, that the complete eradication of a microbial biofilm is crucial for the success of a DAIR procedure. Of course, even a sterile implant surface does not guarantee the final success for this procedure, since bacteria can survive and replicate even within macrophages and other cells of the human host [45, 46]. Nevertheless, the incomplete removal of a biofilm from an artificial surface is a supposable bad precondition to cure any infection.

Therefore, we recommend the use of Er:YAG laser irradiation as an additional tool for surface disinfection of metal implants in PJIs whenever a DAIR procedure seems to be beneficial.

Author Contributions

Lukas K. Kriechbaumer: experimental design, development of the indicated procedures, performing DALIR procedures, data acquisition, analysis and interpretation, statistical analysis, writing, drafting, and revising the manuscript. **Christian Deininger** and **Laura Hruby:** experimental design, data acquisition, analysis and interpretation, statistical analysis, and final approval of the version to be published. **Alexander Planitzer, Marian Mitterer, Patrick Marko, Sebastian Filipp:** performing DALIR procedures, experimental design and data acquisition, analysis and interpretation, final approval of the version to be published. **Wolfgang Happak** and **Gerhild Thalhammer:** experimental design, contribution to the indicated procedures, acquisition, analysis and interpretation of data, final approval of the version to be published, and supervisory support. **Sylvia Nürnberger:** experimental design, data acquisition, SEM investigation, analysis and interpretation, statistical analysis, and final approval of the version to be published. **Gundobert Korn:** experimental design, data acquisition, analysis and interpretation, statistical analysis, performing DALIR procedures and final approval of the version to be published.

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Project Title

Desinfektion mittels Laser-Biofilmabtragung als Behandlungsoption für infizierte Metallimplantate. (english: Laser disinfection as a treatment option for infected metal implants). EK Nr: 1087/2021.

Decision

No objection has been made to the implementation of the study.

German original: Beschluss: Die Ethikkommission befürwortet die Durchführung der klinischen Prüfung mit der Begründung, dass es sich bei dem vorliegenden Projekt um eine relevante Fragestellung handelt, die mit geeigneter Methodik beantwortet werden soll. Die Bewertung des Nutzen/Risikoverhältnisses wird von der Ethikkommission anerkannt. Registration at: http://www.clinicaltrials.gov.

Ethics Statement

The Ethics Committee of Salzburg approved this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Video 1.