Overview on the Evolution of Laser Welding of Vascular and Nervous Tissues

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Received: 4 March 2019; Accepted: 22 May 2019; Published: 27 May 2019

Abstract: Laser welding presents a core position in the health sector. This process has had an outstanding impact on the surgical procedures from many medical areas, such as on vascular and nervous surgeries. The aim of the present research is to present an overview on the evolution of laser welding of vascular and nervous tissues. These surgeries present many advantages, such as an absence of foreign-body reactions and aneurysms and good tensile strengths. However, despite the sutureless nature of the process, complementary sutures have been applied to support the procedure success. An important concern in vascular and nervous laser welding is the thermal damage. The development of temperature-controlled feedback systems has reduced this concern with a very precise control of the laser parameters. The bonding strength of vascular and nerve laser welds can be enhanced with the application of solder solutions, bonding materials, and laser-activated dyes. Alternative techniques to laser welding, such as photochemical tissue bonding and electrosurgical high-frequency technologies, have also been tested for vascular and nervous repairs.

Keywords: laser welding; vascular; nervous; tissue; thermal damage; solder

1. Introduction

Welding technologies are used all over the world in the production of diverse components for several sectors of activity. The demanding manufacturing strategies currently used in industry, which are focused on producing increasingly efficient components, must be supported by an ongoing optimization of the joining processes. Therefore, important research on welding technology is being conducted. As widely spread conventional fusion welding processes are no longer an effective solution for joining some materials and material combinations, the most explored research issue has been the optimization of nonconventional welding processes, such as friction stir welding [1,2], ultrasonic welding [3,4], diffusion welding [5,6], magnetic pulse welding [7,8], laser welding, etc. Laser welding presents excellent characteristics, specifically, its accuracy and high-power density, enabling the production of very localized welds, with minimal distortion and with a residual heat-affected zone. Therefore, laser welding of a large range of cutting-edge materials, such as NiTi shape memory alloys [9,10], Ni-based superalloys [11,12], and Ti alloys [13,14], and material combinations, such as Ta/Mo [15,16], NiTi/CuAlMn [17], NiTi/Ti [18], and Cu/Ti [19], has been intensively studied.

Welding technology is traditionally associated with industrial production. However, it is important to realize that the applications of welding, and especially laser welding, are not restricted to this
field. This process has also presented a core position in the health sector [20–22]. The integration of laser welding in this sector has promoted a revolution in medical practices by enabling the development of safer, earlier, and faster surgical interventions and therapies [23,24]. Actually, medical parameters, such as post-operative pain, narcotics usage, tissue thermal response, and operation time, have been significantly improved [25,26]. Although laser welding in the health sector is not recent, it remains a research topic with extreme relevance and actuality, since improved equipment, procedures, and strategies have been developed in order to define optimized interventions that maximize the patient’s health [27,28]. Significant research on laser-welding procedures has been conducted in a large range of medical areas, such as ophthalmology [29–31], gastroenterology [32,33], urology [34–36], and odontology [37–39].

Laser welding has also had an outstanding impact on nervous and vascular surgeries. These surgeries were some of those in which more outcomes were achieved by the integration of laser-welding technology. However, although important advances have been achieved in this field over the last 30 years, which have enabled laser welding to become a common practice in these surgeries, literature survey and review works on this issue are very incipient in literature. For this reason, the aim of the present research is to present an overview on the evolution of laser welding of vascular and nervous tissues. The fundamentals of the process and the technological evolution registered in this field, concerning the equipment and the adopted procedures and strategies, were analyzed in this research.

2. Laser Welding of Vascular and Nervous Tissues

2.1. Contextualization

Different repair techniques can be applied to nerves, arteries, and veins. The success of these surgeries depends on several factors, such as the severity of the injury, the surgical technique, the surgeon’s experience, and the post-operative biological response [40]. In the most common surgeries (arteriotomies, venotomies, arteriovenous fistulas, and nerve coaptations), the conventional repair procedure is based on sutures. However, as displayed in Table 1, besides the suture-based procedures, different reconstructive techniques, presenting improved operative and post-operative results, have been developed.

Table 1. Techniques for nerve, arteries, and veins repairs.

| Techniques for Nerve, Arteries, and Veins Repairs |
|-----------------------------------------------|
| Conventional techniques                        |
| Suture                                        |
| Nonabsorbable suture [41–43]                   |
| Absorbable suture [41]                         |
| Argon laser welding [41,44]                    |
| CO₂ laser welding [44–47]                      |
| Nd:YAG laser welding [44]                      |
| Laser welding                                  |
| Infrared diode laser welding [48,49]           |
| Potassium titanyl phosphate laser welding [50] |
| Laser welding with intraluminal light source [51] |
| Photochemical tissue bonding [40,52–54]        |
| Electrosurgical high-frequency welding [55]    |

Although the most conventional nonabsorbable sutures are reliable and relatively inexpensive, several studies have pointed to a direct relation between them and post-operative biological problems, such as foreign-body reactions, intimal hyperplasia, and anastomotic stenosis [40–42,45]. In order to minimize these problems, Lawrence et al. [41] compared the application of absorbable and
nonabsorbable sutures. Although similar burst strengths were achieved, the absorbable sutures were found to present an excellent recovery of the blood vessel wall, with minimal inflammatory modifications. However, prior to this study, the medical evolution had already shown results towards a sutureless approach with the integration of laser in medical surgeries. Repair of blood vessels with Nd:YAG laser was achieved in 1979 [56] and, some years later, nerve coaptations by laser welding were successfully reported by White et al. [44,57]. The advantages of laser welding were evident: increased accuracy, decreased operative time, low foreign-body reactions, and a reduction in the formation of post-operative aneurysms. Despite these advantages, which have been corroborated by recent literature [58], many studies have emphasized the relevance of the surgical experience to achieve successful results [41,45,50].

2.2. Welding Procedure

As shown in Figure 1, laser welding occurs when the laser energy induces photomechanical and photothermal tissue modifications, mainly due to its capability for selective modulation of the biologic functions of cells. According to various studies [59–61], the tissue remodeling process is characterized by the equilibrium between extracellular matrix (ECM) remodeling and collagen biosynthesis. This balance is achieved through the thermal response of three main biologic structures: matrix metalloproteinases (MMPs) [62,63], transforming growth factors (TGFs) [64,65], and heat-shock proteins (HSPs) [66,67]. When observing collagen biosynthesis, Nagata [67] and DeBruler et al. [68] showed that HSP 47 is responsible for producing neocollagenesis that will benefit tissue remodeling. In turn, Wang and Khalil [62] and Nesi-Reis et al. [69] stated that MMPs have an important role in vascular tissue remodeling, since their activation will act upon collagen degradation and ECM transformations. Additionally, positive results on collagen expression and an increased number of new growing vessels were recently reported by Fortuna et al. [70] through the application of the 670 nm GaAlAs laser.

Figure 1. Schematics of laser welding of a nervous tissue [40].

Considering the ECM transformations and collagen biosynthesis, laser irradiation focuses on structural proteins, resulting in the protein denaturation process at temperatures between 60 °C and 65 °C [41,44,71,72]. When the temperature exceeds 65 °C, the fusion with laser does not serve its purpose and cell degeneration takes place, primarily through vaporization at 100 °C, and finally through burn or disruption at higher temperatures [41,44,71,72]. Thus, the optimization of the laser power and the exposure time is required to achieve the cross-linking fusion of the collagen fibrins, which is directly related to the success of the welding operation [41,42,44,55].

Despite the precision and the efficiency of laser welding in vascular and nerve surgeries, thermal damage of the cells may occur, i.e., damage without possible regeneration, which results in a low tensile strength of the bonding area. Thermal tissue degeneration is directly related to laser parameters and biological conditions, mainly with the laser exposure time and the absorptive properties of the bonding region. Equilibrium of these factors is crucial to achieve improved results [47,49]. Moreover, it has been concluded that variables, such as the laser wavelength, the depth of tissue penetration, the energy fluency, and the use of cooling solutions, also influence the success of the surgery [40,44,45]. Several strategies have been tested in laser-welding procedures in order to minimize the thermal
damage of the tissues, specifically, the use of thermal feedback systems, saline solutions, and different irradiation techniques.

The use of thermal feedback systems is a very effective strategy for preventing thermal damage, as they enable the monitoring of the temperature in the weld region, with a very precise control of the laser parameters [42,45,47,52,73]. Regarding the use of saline solutions, although Menosky et al. [45] reported that it could decrease the bonding strength of the weld, many other studies demonstrated that it had no implications on this property, being an effective strategy for cooling down the welding site [41,42,57,71]. Another strategy was tested by Pabittei et al. [72], who compared different irradiation techniques in vascular repairs, specifically, laser-welding scanning and single-spot laser welding. According to these authors, the single-spot method may be more beneficial when applied through multiple laser pulses in the surgical area, enabling tissue to cool down between pulses, and therefore, decreasing the thermal damage. Research has also been conducted to predict tissue damage and the corresponding effect by a finite element method, which may provide useful pre-operative information for the laser-welding procedure [74].

In laser welding of vascular and nervous tissues, it is also very important to consider the tissue apposition, i.e., the position of the adjacent tissues in which the welding procedure occurs, since it determines the quality of the bonding of the collagen fibrils [45,71,73]. In order to improve the welding conditions, traction sutures can be used to approximate the tissues, enabling higher bonding strengths to be achieved [42,47,57,71,73]. In turn, Nakadate et al. [48], in laser-assisted vessel repair (LAVR), reported the beneficial effect of preloaded longitudinal compression on the weld strength. These authors reported a success rate of 83% when compared to welds in which preloaded compression was absent. Figure 2 shows the instrumentation used by them, in which the vessel clamp device (Figure 2a) used for the application of the longitudinal compression in the pre-operative welding repair (Figure 2b) can be observed. Additionally, Table 2 summarizes results from previous works on vascular laser welding in which the use of complementary sutures was studied. Barton et al. [40] and Kramer and Rentschler [58] recently stated that many surgeons still use additional sutures as a complement to the laser-welding techniques.

![Figure 2](image)

**Figure 2.** Instrumentation for preloaded longitudinal compression: (a) Vessel clamp device (prototype); (b) Procedure of preloaded longitudinal compression [48].

| Study                  | Total No. of Welds | No. of Welds with Complementary Sutures | No. of Additional Sutures Per Weld |
|------------------------|--------------------|---------------------------------------|-----------------------------------|
| White et al. [44]      | 5                  | 1                                     | 1                                 |
| White et al. [57]      | 12                 | 12                                    | 1                                 |
| White et al. [71]      | 24                 | 12                                    | 1 to 2                            |
| Lawrence et al. [41]   | 61                 | 55                                    | 1                                 |
| Hasegawa et al. [42]   | 12                 | 8                                     | 1 to 3                            |

*—only the welds produced with argon laser were considered.
Another crucial aspect in vascular and nervous surgeries consists of the analysis of the end point of laser welding. The most conventional method is visual feedback. Chuck et al. [56] and Menosky et al. [45] created visual identification scores to correlate the different argon-laser parameters, and the resulting end points, with the response of the tissue. Figure 3 shows the stages of welded end points, with the “whitening” and the “beginning of caramelization” being the most adequate appearances [45,47,56,73].

![Figure 3. Visual identification scores and adequate laser-welding end point [45,56].](image)

In addition to visual feedback, other methods have been developed to analyze the end point of laser welding. The most reported method consists of measuring the temperature using thermal feedback systems [42,45]. As reported above, these systems are also associated with the prevention of tissue weakening by thermal damage [51].

### 2.3. Laser Technology

According to literature, the most commonly used medical lasers are CO$_2$, argon, and Nd:YAG. The CO$_2$ and argon lasers are those with the most suitable application in medical surgeries due to their laser properties and their biological compatibility [40,41,46,73]. The application of these lasers is characterized by their coagulation, vaporization, and disruption capabilities [44]. Considering the published research on laser welding of vascular and nervous tissues, it is possible to define the most reported surgical application for each type of laser. The main applications, advantages, and drawbacks of CO$_2$, argon, and Nd:YAG lasers are displayed in Table 3.

| Laser   | Suitable Surgeries | Advantages                                      | Drawbacks                                      |
|---------|--------------------|-------------------------------------------------|------------------------------------------------|
| Argon   | Vascular repairs   | Deep vessel wall penetration with lower energy output [41] | Nerve absorption of laser light is minimum due to the lack of presence of significant chromophores [73] |
| CO$_2$  | Nerve repairs      | High energy output [41]                          | Used primarily to cut and vaporize tissue [44]  |
|         |                    | Low penetration depth [45]                       | Low strength in arterial repairs, cannot sustain systemic pressures [57] |
| Nd:YAG  | Vascular repairs   | Easy penetration of the tissue [44]              | Limited to microvascular anastomoses surgeries [41] |
|         |                    |                                                 | Produces deep uncontrolled thermal injury due to excessive energy density [44] |
|         |                    |                                                 | Low strength in arterial repairs, cannot sustain systemic pressures [57] |

An overview of the histological results of CO$_2$ and argon repairs over conventional suturing is summarized in Table 4. Regarding the vascular argon laser-welding repairs, the results are superior when compared to conventional suture application. White et al. [44] reported that the biological effects
of argon laser welding in vascular healing presented a minimal inflammatory response, near normal collagen content, and no aneurysm formation. The optimal vascular results of argon laser welding have been corroborated by other authors along the years [41,42,57,71]. Nervous CO\(_2\) laser-welding repairs also presented evolutionary results. Specifically, Bhatt et al. [50] concluded that CO\(_2\) laser-welded nerve coaptations can be performed with higher functional recovery rates than those achieved by nerve sutures. Additionally, Leclère et al. [75] and Nakadate et al. [48] showed that the use of infrared (IR) diode lasers can be excellent alternatives. At wavelengths of 1450, 1940 and 1950 nm, water presents high absorption coefficients, which enables laser-welding repairs to be performed without additional materials, while still obtaining good surgical results, such as minimal aneurysm formation. Another alternative to CO\(_2\) and argon laser welding can be the potassium titanyl phosphate (KTP) laser-welding technique. According to Bhatt et al. [50], it has a better functional recovery than CO\(_2\) laser welding, i.e., 92.4% against 86.8%.

### Table 4. Overview of histological results of CO\(_2\) and argon repairs over conventional suturing.

| Study            | Laser Welding | Histologic Examination                                                                 |
|------------------|---------------|----------------------------------------------------------------------------------------|
|                  | CO\(_2\)      | Argon                                   |                                             |
| White et al. [44]| -             | x                                       | Minimal inflammatory response, near normal collagen content, absent of aneurysm formation |
| White et al. [57]| -             | x                                       | Absent of hematomas, false aneurysms or luminal dilatation, and minimal inflammatory response |
| White et al. [71]| -             | x                                       | Minimal inflammatory response and near-normal collagen content |
| Lawrence et al. [41]| -         | x                                       | Absent aneurysm formation                   |
| Menosky et al. [45]| x            | -                                       | Absent foreign body reaction, minimized scar tissue formation |
| Happak et al. [46]| x            | -                                       | Minimized tissue thermal damage and no foreign body reactions |
| Hasegawa et al. [42]| -            | x                                       | Absent aneurysm formation although with no complete regeneration of the elastic lamina |
| Jonge et al. [47]| x             | -                                       | Minimal thermal necrosis and welding strength increase |
| Bhatt et al. [50]| x             | -                                       | Good functional recovery with no nerve dehiscence |

### 2.4. Welding Parameters and Bonding Conditions

An overview of the main researches conducted in vascular and nervous laser welding over the last 30 years is presented in Table 5. The laser type and the main parameters tested in these works are displayed in the table. The research has been mainly focused on optimizing the inverse relation existing between the laser power and the exposure time by testing different laser types (different wavelengths). Regarding the laser operation mode, continuous wave (CW) was used in most of the studies, although the laser was often performed as a sequence of consecutive pulses (not short-pulse laser mode) by the actuation of a switch device, like, for example, a foot switch. For this reason, the table presents the weld time, which corresponds to the total time per weld, the time of each pulse, and the interval between consecutive pulses. It should be noted that the tested conditions are not generalizable, since they strongly depend on the specific application, and consequently, on the interaction mechanisms between the laser radiation and the welded tissues. The application of external bonding materials, protein solutions (solders), and dyes in the weld region has also been intensively studied (Figure 4).
Table 5. Chronological overview of laser-welding results in vascular and nerve repair.

| Study            | Surgery  | Laser Type              | Laser Mode | Welding Parameters | Time          |
|------------------|----------|-------------------------|------------|-------------------|---------------|
|                  |          |                         |            | Wavelength (nm)   | Power (W)     | Weld Time (s) | Pulse Time (s) | Pulse Interval (s) |
| White et al. [44]| Vascular | Argon                   | CW         | 458–515           | 1.5           | 300–400       | NR             | NR              |
|                  |          | CO₂                     | CW         | 10,600            | 1–2           | 20–40         | NR             | NR              |
|                  |          | Nd:YAG                  | CW         | 1060              | 7             | 20–25         | NR             | NR              |
| White et al. [57]| Vascular | Argon                   | CW         | NR                | 0.5           | 240           | 5              | 0.2             |
| White et al. [71]| Vascular | Argon                   | CW         | NR                | 0.5           | 125–150       | 5              | 0.2             |
| Chuck et al. [56]| Vascular | Argon                   | CW         | 488               | 0.01–0.05     | 15–120        | NR             | NR              |
| Lawrence et al. [41]| Vascular | Argon                   | CW         | NR                | 0.75          | 100           | 5              | 0.2             |
| Menosky et al. [45]| Nerve    | CO₂                     | CW         | NR                | 0.05–0.15     | NR            | 0.1–3          | NR              |
| Curtis et al. [43]| Nerve    | IR diode                | CW         | 810               | 0.08          | NR            | NR             | NR              |
| Happak et al. [46]| Nerve    | CO₂ with power          | CW         | NR                | 0.06          | NR            | NR             | NR              |
|                  |          | reduction unit          |            |                   |               |               | NR             | NR              |
| Hasegawa et al. [42]| Vascular | Argon                   | CW         | NR                | 0.17          | NR            | 5              | NR              |
| Stewart et al. [76]| Vascular | IR diode                | CW         | 808               | 0.08          | 4 × 0.5       | NR             | NR              |
| Ott et al. [51]  | Vascular | IR diode                | CW         | 808               | 0.41          | 30            | NR             | NR              |
|                  |          |                         |            |                   | 0.55          | 45            | NR             | NR              |
| O’Neill et al. [52]| Vascular | PTB with Nd:YAG         | CW         | 532               | 0.35          | 2 × 30        | NR             | NR              |
| Jonge et al. [47]| Vascular | CO₂                     | CW         | 10,600            | 0.17          | 261 ± 40      | NR             | NR              |
| Bogani et al. [77]| Vascular | IR diode                | CW         | 808               | 0.4–3         | 2.5–30        | NR             | NR              |
| Pabittei et al. [72]| Vascular | IR diode single-spot   | CW         | 670               | 1.6           | 50            | NR             | NR              |
|                  |          | scanning                |            |                   |               | 82            | NR             | NR              |
| Pabittei et al. [49]| Vascular | IR diode                | CW         | 670               | 0.096         | NR            | 25             | NR              |
| Nakadate et al. [48]| Vascular | IR diode                | CW         | 970               | 2.4           | 30            | NR             | NR              |
| Bhatt et al. [50] | Vascular | CO₂                     | CW         | 10,600            | 0.1           | NR            | 1              | NR              |
|                  |          | KTP                     | CW         | 532               | 3–4           | NR            | 1              | NR              |
| Hiebl et al. [78] | Vascular | IR diode                | CW         | 808               | 0.25–1.5      | 30            | NR             | NR              |

NR—Non-referred.

Figure 4. Schematics of laser welding of a nervous tissue, with the application of a solder and a light absorbing dye [40].

The materials referred to above improve the technical parameters and reduce the thermal damage, enabling the achievement of higher weld strength [43,46,72,76]. Menosky et al. [45] concluded that the amount and concentration of structural proteins is directly correlated with the bonding strength of the welded repair. This correlation has been recently corroborated by Hiebl et al. [78]. The different types of bonding materials and solders reported to be used in nervous and vascular repairs are displayed in Table 6. Although the biodegradable glues (fibrin and cyanoacrylate glues and polyethylene glycol)
have initially been used with success, due to reduced inflammatory reactions and easy application, they should be avoided because of their rigidity, cytotoxicity, and risk of infection [40,51,58]. Moreover, the development of albumin-based solution solders allowed higher biocompatibility between its proteinaceous structure and collagen fibers. As its application is possible with different variations in composition, this solder solution is the most common in these procedures [40,46,72,76]. For example, BioGlue, which is composed of 45% bovine serum albumin and 10% glutaraldehyde, cross-links with tissue fibers through chemical bindings, allowing vascular chemical stabilization of sutured and welded sites [58].

**Table 6.** Advantages and drawbacks of solders and bonding materials used in vascular and nerve repairs.

| Bonding Materials and Solders | Advantages | Drawbacks |
|-------------------------------|------------|-----------|
| Fibrin glue [40]             | Reduces inflammatory tissues and easy application | Low tensile strength, infection risk |
| Cyanoacrylate glue [40,58]   | High tensile strength and easy application | Requires support stay sutures, causes fibrosis, foreign-body toxicity |
| Polyethylene glycol (PEG) [40] | Nontoxic, biocompatible and reduces scar tissue | Slow degradation process (over 20 months) |
| Albumin-based solution [40,47,78] | In nerve repairs, protects the epineurium, increases bonding strength, reduces thermal damage | Leakage of fluid solder, thermal damage still present, viral infection risk, becomes brittle |

Important research has been conducted in the application of solder solutions in vascular and nerve tissue welding. Menosky et al. [45] compared different types of solders in laser nerve welding. They observed an increased bonding strength with dried albumin, 20% albumin and egg white solutions, when compared to welding alone and to welding with fibrin-glue repairs. No improvement in bonding strength was achieved with an application of a 5% albumin solution. In turn, Curtis et al. [43] reported that leakage of liquid solder solutions occurred during surgery, creating an obstacle to the regeneration process. In agreement with this, Jonge et al. [47] observed that the disruption of low-viscosity solder solutions occurred at the solder midline. However, regarding semi-solid solder solutions, the same authors reported that these solutions withstand higher pressures in the solder area than at the interface, due to higher protein concentrations. The application of a semi-solid solder solution in arterial laser welding is illustrated in Figure 5. As illustrated by the black dots, although laser welding is a highly localized process, a heat-affected zone (HAZ) was generated around the welding site, which agrees well with the aforementioned concerns regarding thermal damage.

![Figure 5. Transverse cross-section of an artery repaired by laser welding, with the application of a semi-solid solder solution [47].](image-url)
Bogni et al. [77] and Pabittei et al. [72] focused their works on minimizing solder leakage by using biodegradable polymers as carrier material for the liquid solders and by studying solder viscosity, respectively. In agreement with the previous researches, Pabittei et al. [49] reported that the application of semi-solid solders provides higher protein density and cohesive bonding when compared to fluid solders. The authors also reported that porous polymer scaffolds can be used to prevent solder leakage. In turn, Barton et al. [40] confirmed the possibility of including support cross-linking agents, such as genipin, in albumin-based solutions to improve their flexibility and reduce brittleness. The improvement of solder properties by adding other elements had already been tested some years earlier by Stewart et al. [76], who introduced heparin in an albumin-based solder with the purpose of reducing microvessel thromboses. More recently, Hiebl et al. [78] reported the effectiveness of using carrier membranes with bovine serum albumin (BSA) solder linked by covalent cross-linking bindings and indocyanine green (ICG) dye to improve bonding strength and to prevent liquid solder leakage. In fact, the addition of laser-activated dyes in solder solutions (ICG and fluorescein isothiacyanate), enabling the use of lower energy outputs due to selective laser absorption, which minimizes the associated thermal damage, had already been reported in previous works, such as Chuck et al. [56], Curtis et al. [43], and Ott et al. [51].

Besides the welding parameters and the use of solder solutions, the welding process is also influenced by other issues. Specifically, handling laser welding in three-dimensional (3D) approaches requires specific surgical skills due to the necessary manipulation of the vascular and nervous elements, which may lead to injury aggravation and procedure repetition [50,51]. To avoid manual surgical manipulation in the laser-welding procedure, Ott et al. [51] presented a different surgical approach, which is shown in Figure 6. This strategy consists of the insertion of a laser fiber implemented in a balloon catheter, allowing a 360° laser irradiation over a two-layer soldering procedure. Eleven successful welds in fourteen executed were reported by these authors. In turn, Pabittei et al. [49] also reported that a laser fiber that delivers a 360° laser irradiation can also diminish the thermal damage.

![Figure 6. Schematics of the laser-assisted vessel soldering [51].](image)

As described above, important progress has been registered in laser welding of nervous and vascular tissues. Therefore, the development of fiber lasers is of great importance to the laser-welding technique, mostly due to their advantages, such as excellent heat dissipation, beam quality, and efficiency [79,80]. Because of their diversified operating modes, wavelengths, and energy levels, different fiber lasers, such as erbium-, thulium-, holmium-, and ytterbium-doped families, can be used, for example, in microsurgeries of soft tissues [80,81]. The effect of these lasers in soft tissues can range from ablative purposes to regenerative procedures like laser welding [82]. In terms of medical applications, various studies have proven their suitability for photodynamic therapies, biomedical sensing, as well as for other procedures in the vascular and dentistry fields [81,83,84].

Although laser-welding improvements have been achieved with solder solutions, laser-activated dyes, intraluminal devices with 360° laser irradiation, etc., inherent thermal damage is still present. As an alternative to thermal laser welding, photochemical tissue bonding (PTB) does not inflict any thermal
damage to the welded and surrounding tissues. With this technique, sealing of tissue is achieved through the use of dyes that are chemically activated, such as Rose Bengal (RB) dye and Riboflavin-5-Phosphate, allowing the formation of fiber cross-linking bindings [53,54]. Results showed no operative and post-operative bleeding, absence of aneurysms, and high tensile strength [40,49,52,54,58]. Moreover, electrosurgical high-frequency (ESHF) technology has already been tested as an alternative technique to laser photothermal and photochemical mechanisms. Korsak and Chaikovskii [55] presented an animal study in which peripheral nerve repairs were made by welding soft tissues with high-frequency current. A similar morphology was achieved in sutured and high-frequency (HF)-welded nerves, with beneficial effects of ESHF welding in terms of the regeneration process.

It should also be noted that new research directions are starting to emerge within these surgical practices. Auxiliary technological devices and instrumentation, such as robotic-assisted surgeries with enhanced image-processing systems [85–87], as well as the development of new biomaterials based on nanotechnology [88,89], show a great potential for driving the future evolution of reconstructive vascular and nervous laser welding.

3. Conclusions

An overview on the evolution of vascular and nervous surgeries by laser welding was presented in this research. The fundamentals of the process and the technological evolution registered in this field were analyzed. The following conclusions can be drawn:

- Although laser welding presents many advantages, such as increased accuracy, decreased operative time, reduction of foreign-body reactions, and reduction of aneurysms formation, an accurate control of several process variables is required. The laser type and parameters, the exposure time, the tissue apposition, the temperature, and the absorptive conditions present high relevance.
- Thermal damage may occur in vascular and nervous laser welding. Different strategies have been tested to overcome this concern. Temperature-controlled feedback systems present the advantage of reducing the thermal damage with a very precise control of the laser parameters.
- The bonding strength of vascular and nerve welds can be enhanced with the application of solder solutions, bonding materials, and laser-activated dyes. The use of dyes with albumin-based solution solders has presented an especially beneficial effect on the welding conditions.
- Alternative techniques to thermal laser welding, such as photochemical tissue bonding and electrosurgical high-frequency technologies, have been tested for vascular and nervous repairs.

Author Contributions: Conceptualization, D.F.G., I.G., M.A.R.L.; methodology, D.F.G., I.G., M.A.R.L.; formal analysis, D.F.G., I.G., M.A.R.L.; investigation, D.F.G., I.G., M.A.R.L.; writing—original draft preparation, D.F.G.; writing—review and editing, D.F.G., I.G., M.A.R.L.; supervision, I.G., M.A.R.L.

Funding: This research received no external funding.

Acknowledgments: The authors acknowledge the support of ISEL-Polytechnic Institute of Lisbon, CIMOSM, CEMMPRE, IDMEC, and NOVA UNIDEMI. The third author also acknowledges the support of FCT through IDMEC, LAETA, project UID/EMS/50022/2019.

Conflicts of Interest: The authors declare no conflict of interest.

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