Article

Recent Advances in Laser Technology - Corneal Refractive Surgery

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Abstract: Corneal refractive surgery, a pivotal field in ophthalmology, aims to correct visual impairments like myopia, hyperopia, and astigmatism by corneal modification. This paper explores the evolution and advancements in this domain, particularly highlighting the transition from gas- and excimer lasers to solid-state ultraviolet lasers. The latter are praised for their precision, reduced thermal damage, and faster recovery, transforming surgical outcomes and patient satisfaction. Additionally, the integration of diagnostic technologies such as wavefront analysis and corneal topography has further refined surgical precision. This study also addresses the comparative safety and effectiveness of different laser wavelengths on the cornea, underscoring the minimized risks and enhanced recovery associated with solid-state lasers. Our findings advocate for the increasing adoption of solid-state UV lasers in refractive surgeries due to their significant benefits over traditional methods, despite existing limitations such as cost and the need for specialized training.

Keywords: laser technology, ophthalmology, solid-state ultraviolet lasers, ablative solid-state lasers

1 | INTRODUCTION

Corneal Refractive Surgery, a modern discipline within ophthalmology, addresses visual impairments such as myopia (nearsightedness), hyperopia (farsightedness) and astigmatism through the modification of the corneal structure. This branch of medicine has experienced substantial advancements over the past decades, predominantly attributed to the incorporation of laser technology [1].

Exploring the impacts of laser light on biological tissues commenced in the early 1980s. Through experimental research, the ability of laser beams to alter the corneal surface's curvature by phototherapeutic ablation was established. The pioneering laser treatments in ophthalmology used gas lasers, specifically valued for their precision, reliability, affordability, longevity, and consistent energy output parameters [2]. In particular, excimer lasers, initially employed within defense and electronics sectors, emit a wavelength (λ) of 193 nm. This specific wavelength is exceptionally safe for ocular structures due to its limited penetration depth (2 – 3 μm) and its complete absorption by corneal collagen. Additionally, the short-pulse emissions from excimer lasers result in minimal DNA damage, significantly reducing any risk of mutagenesis or carcinogenesis.

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With the evolution of laser technology (Fig. 1), the emphasis shifted towards excimer lasers for intricate procedures like LASIK (Laser-Assisted in Situ Keratomileusis). However, despite technological strides, challenges such as extended recovery times and potential complications remained [3].

In the contemporary landscape, solid-state ultraviolet lasers have emerged as increasingly favored tools in refractive surgery, prized for their precision and safety. The utilization of ultraviolet light allows for unprecedented accuracy with negligible thermal influence, thus mitigating the risk of injury to adjacent tissues and expediting the rehabilitation process for patients.

Furthermore, advancements in diagnostic and mapping technologies have complemented these surgical improvements, allowing for personalized and precise corneal reshaping. The integration of wavefront analysis and corneal topography has facilitated a more refined understanding of aberrations and irregularities [4]. Consequently, this has allowed for the development of customized surgical approaches, improving visual outcomes and patient satisfaction. As research continues, the potential for minimally invasive techniques and novel laser technologies holds the promise of further revolutionizing corneal refractive surgery, making it an even safer and more effective option to correct vision.

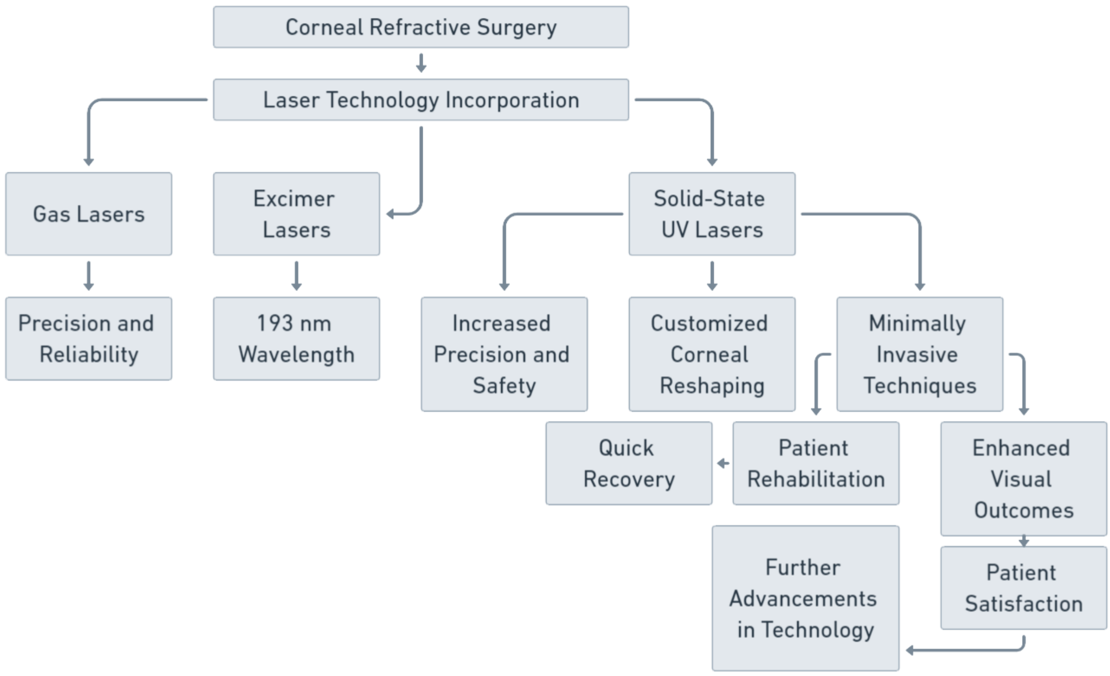

Fig. 1. Evolution of Corneal Refractive Surgery

2 | LASERS IN REFRACTIVE CORNEAL SURGERY

Solid-state ultraviolet (UV) lasers represent cutting-edge technology increasingly utilized across various medical fields, particularly in ophthalmology [5]. These lasers employ solid media, such as crystals or glasses doped with rare-earth element ions, to generate UV radiation. Contrary to traditional gas and excimer lasers [6], solid-state devices offer enhanced stability, longevity, and precision. In the UV spectrum, particular attention is given to ions like Neodymium (Nd) or Erbium (Er), facilitating the production of short wavelengths of light, ideal for precise and minimally invasive surgical procedures.

UV lasers are characterized by their short wavelength, ranging from 193 to 355 nanometers, making them particularly useful for precise ablative procedures. The short wavelength allows for controlled and precise removal of microscopic tissue layers without significant thermal impact on surrounding areas.

In the realm of refractive surgery, the main competitors to solid-state UV lasers are excimer lasers, which also operate within the UV spectrum but utilize a gas medium to generate their beam. Although excimer lasers were groundbreaking at their inception, their solid-state counterparts offer several advantages, including lower cost of ownership, smaller size, and greater reliability.

The application of UV lasers in ophthalmology is predicated on their ability to photobleach, a process wherein molecular bonds within tissues are disrupted under the influence of ultraviolet radiation. This enables the performance of refractive procedures with high precision, while minimizing the risk of thermal damage and speeding up the healing process [5].

Solid-state UV lasers are applied in a variety of refractive procedures, including LASIK, PRK (Photorefractive Keratectomy), and LASEK (Laser Assisted Sub-Epithelial Keratectomy) [7]. Each procedure varies in technique and degree of intervention, but all aim to modify the shape of the cornea to correct vision.

LASIK: This is the most popular procedure, where a thin flap is initially created in the cornea, followed by the use of a UV laser to reshape the inner layers. Solid-state lasers provide high precision and control in flap creation and ablation, leading to improved outcomes and accelerated recovery.

PRK and LASEK: Unlike LASIK, these procedures do not involve the creation of a flap. Instead, solid-state UV lasers directly ablate the superficial layers. These methods are considered less invasive and may be more suitable for patients with thin corneas or other specific conditions.

The advent of solid-state UV laser technology marks a significant milestone in medical advancements, offering a safer, more efficient alternative to previous methodologies. Their introduction has revolutionized ophthalmic surgeries, providing patients with faster recovery times and improved outcomes. As technology progresses, solid-state UV lasers will find broader applications in medicine, further underscoring their significance in enhancing patient care and treatment precision. This ongoing innovation underscores a transformative era in surgical precision and patient outcomes, which has broader implications for healthcare and therapeutic techniques.

Studies [8] indicate that the use of solid state UV lasers in refractive surgery results in a high degree of patient satisfaction, improved vision without the need for glasses or contact lenses, and a low percentage of complications. The key factors for success include the precision of the laser application and minimal thermal damage.

Compared to other vision correction methods, such as contact lenses or glasses, laser correction offers a long-term solution to vision problems. While glasses and lenses merely adjust visibility, refractive surgery alters the physical shape of the eye, addressing the root cause of impaired vision.

Solid-State UV lasers in Refractive Surgery exhibit distinct advantages as well as certain limitations, marking a significant advancement in ophthalmological procedures while also presenting areas for potential improvement (Fig. 2).

Advantages: Solid-state ultraviolet lasers present numerous significant benefits in the context of refractive surgery:

- Precision and Controllability: Owing to their short wavelength, UV lasers enable high-precision ablation, which is critically important for vision correction. This allows surgeons to accurately shape the cornea according to the individual needs of the patient.
- Minimization of Thermal Damage: UV lasers result in less thermal damage to surrounding tissues, reducing the risk of inflammation and accelerating post-operative recovery.
- Versatility: Solid-state UV lasers can be employed in various types of refractive procedures, making them a valuable tool in the ophthalmologist's arsenal.
- Safety and Effectiveness: Numerous clinical studies have validated the safety and effectiveness of UV lasers for vision correction, leading to their widespread adoption in ophthalmologic practice.

Limitations: Despite their numerous advantages, solid-state UV lasers also possess certain limitations:

- Cost: The high cost of equipment and maintenance can be a barrier for some medical facilities, particularly in low- and middle-income countries.
- Training Requirements: The high degree of precision and control provided by UV lasers demands a corresponding level of skill and training for surgeons.
- Not Suitable for All Patients: Despite a wide range of applications, there are specific limitations to the use of refractive surgery, including age, corneal thickness, and overall eye health.

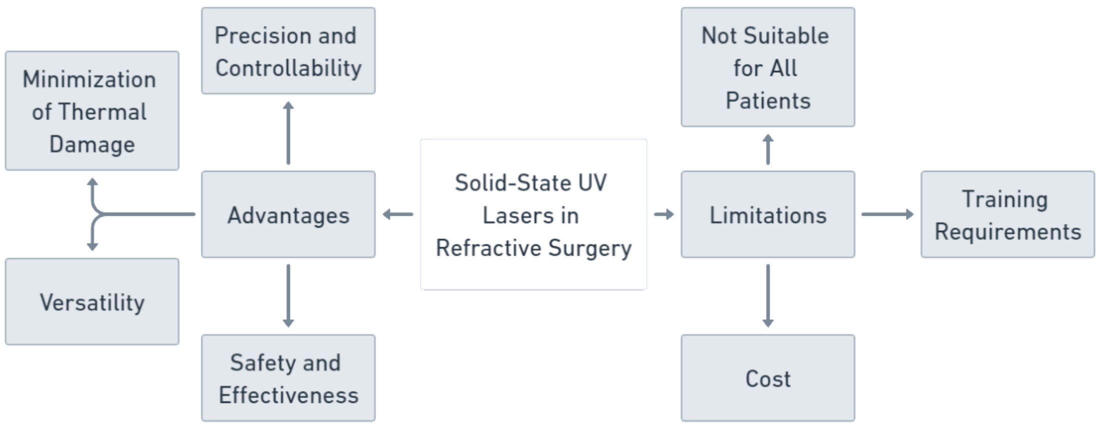

Fig. 2. Advantages and limitations of Solid-State UV Lasers in Refractive Surgery

Currently, ArF excimer lasers hold a leading position in refractive surgery, with all their advantages being thoroughly studied and utilized [9]. The enhancement of excimers is progressing towards increasing pulse generation frequency, optimizing the shaping scheme based on the "flying spot" principle, and enhancing the frequency of active eye-tracking video systems, all of which improve the quality of operations and facilitate the surgeon's work. Nonetheless, the search continues for other types of laser radiation that similarly affect the cornea but reduce or eliminate inconveniences due to the technical features of the construction and operation of excimer lasers. In particular, one of the operational challenges of excimer lasers is the need for constant refilling with a gas mixture containing toxic fluorine. Moreover, the drawback of radiation with a wavelength λ=193 nm is its high absorption by oxygen molecules and water vapor, leading to ozone formation, which, in turn, also absorbs ultraviolet, resulting in laser energy shielding.

It is also known that air humidity and corneal hydration levels affect ablation efficiency [10]. Every ophthalmic surgeon performing refractive operations is aware that a hyperhydrated stromal layer of the cornea reduces the strength of ablation, and surgery on an overly dry cornea can lead to a hypercorrection effect. A clear example is when excessive fluid accumulation at the flap hinge leads to induced irregular astigmatism due to uneven ablation. This requires constant control of the operating room microclimate, conducting calibration tests, and visual monitoring of the degree and uniformity of corneal hydration. Given the above, efforts to find a more "user-friendly" laser radiation source are justified, relevant, and represent a wide field of activity for theoretical and practical ophthalmology.

At the end of the last century, the solid-state ultraviolet laser Novatec LightBlade was developed in the USA, generating radiation with a wavelength λ=210 nm [11]. However, it is worth noting the inefficiency of solid-state lasers due to the nonlinear rapid failure of the laser crystal and the labor-intensive process of its replacement. Nevertheless, since the beginning of 2015, the next generation of solid-state lasers has emerged: the diode Nd: YAG laser Pulzar Z1 (CustomVis) with a wavelength λ=213 nm and the diode λ=210 nm laser LaserSoft (Katana Technologies). The results obtained with their use suggest a safe and high-quality impact on the cornea. [8, 12]

When addressing the safety of radiation with a wavelength longer than λ=193 nm, its penetrating ability into eye tissues should be clarified. According to data, UV radiation up to λ=230 nm is completely absorbed by the cornea and does not penetrate the inner sections of the eye. This is also confirmed by research results. At the same time, it indicates the cornea's ability to fully absorb radiation in an even broader spectrum – up to λ=280 nm. Consequently, radiation with wavelengths λ=210, λ=213, and even λ=223 nm is absolutely safe for the deeper structures of the eyeball.

Regarding the direct impact of radiation in the spectrum λ=193 – 223 nm on the cornea, several studies indicate its minimal damaging effect [13, 14]. In particular, in vivo studies have examined rabbit corneas after ablation with excimer (λ=193 nm) and solid-state lasers (λ=213nm). Thermal damage was assessed using light microscopy, while unintended DNA synthesis, reflecting the degree of DNA damage in each cell, was evaluated through autoradiography. The studies did not show significant differences in the parameters tested between radiation with λ=193 nm and λ=213 nm. The absence of damaging thermal action was confirmed: the results indicate a minimum of undesirable scarring changes in the corneal tissue and its good healing. It has also been established that both wavelengths induce comparatively low levels of DNA damage (in both cases, unintended DNA synthesis was detected in less than 4% of corneal cells), therefore, not causing significant mutations or oncogenic transformation of the tissue. The minor level of impact by laser radiation with λ=193 nm is explained by the presence of cytoplasmic membrane components shielding the cell nucleus from this wavelength, thus limiting the dose of photons reaching the cell's DNA. The authors suggest that this same mechanism provides cell protection against radiation with a wavelength λ=213 nm [4, 13, 14].

In turn, a comparative evaluation of the clinical efficacy and safety of human corneal exposure to radiation with wavelengths λ=193 and λ=223 nm was conducted [13]. The study not only the equal clinical efficacy of both wavelengths in correcting myopia but also the absence of significant changes in the biochemical indicators of tear fluid before and after corneal photoablation (antibodies to native DNA antigens, lactoferrin, circulating immune complexes). The results of laboratory studies suggest that radiation with wavelengths λ=193 and λ=223 nm does not cause the development of destructive inflammatory processes or activation of the immune response in the human cornea.

The study [8,12] examined the impact of solid-state laser radiation (λ=213 nm) on the condition of the corneal endothelium. Analysis of endothelial cell density was conducted before surgery and over 12 months post-operation using photorefractive keratectomy (PRK) techniques for moderate myopia on excimer and solid-state lasers. No significant differences in this parameter were observed between these two groups at the corresponding observation times, which also confirms the absence of damaging effects on the cornea from radiation with λ=213 nm [1, 6, 14].

All of the above indicate the safety of radiation with a wavelength of λ=213 nm for the cornea and inner eye structures and the feasibility of using this type of radiation for photorefractive operations. To date, the scientific literature contains information on a considerable accumulated experience, as well as observations on the condition of patients' eyes operated using the solid-state laser Pulzar Z1 (CustomVis), sufficient to assess not only the safety, but also the quality of the interventions. This system is operational in more than 20 centers [8, 12]. The capabilities of this device, indications for surgery, and advantages of the laser are actively utilized. Stable clinical results have been obtained in the correction of irregular astigmatism, mild and moderate myopia, and myopic astigmatism. All authors noted the high precision of the laser, the ability to form a smooth ablative profile of the cornea, and minimal damaging thermal and mechanical effects on the cornea.

Addressing the advantages of the solid-state laser, it is essential to revisit the issue of corneal hydration. We have noted that corneal hydration, the presence of a fluid layer on its surface, and increased humidity in operating air are factors that significantly affect ablation strength when operating with wavelength λ=193 nm. Conducted studies have demonstrated that, firstly, the wavelength λ=213 nm is closer to the peak absorption of corneal collagen and, secondly, it is weakly absorbed by water, physiological solution, and balanced salt solution (BSS). The research revealed a significant difference in the absorption coefficients for these solutions and in the penetration depth for radiation with wavelengths λ=193 and λ=213 nm. It was established that radiation with λ=213 nm is extremely weakly absorbed by 0.9% sodium chloride solution and balanced salt solution, while for radiation with λ=193 nm, these liquids act as strong absorbers.

Figure 3 summarize an overview of the advancements in corneal refractive surgery, detailing the evolution of laser technology, different surgical procedures, advancements, and challenges with solutions in the field.

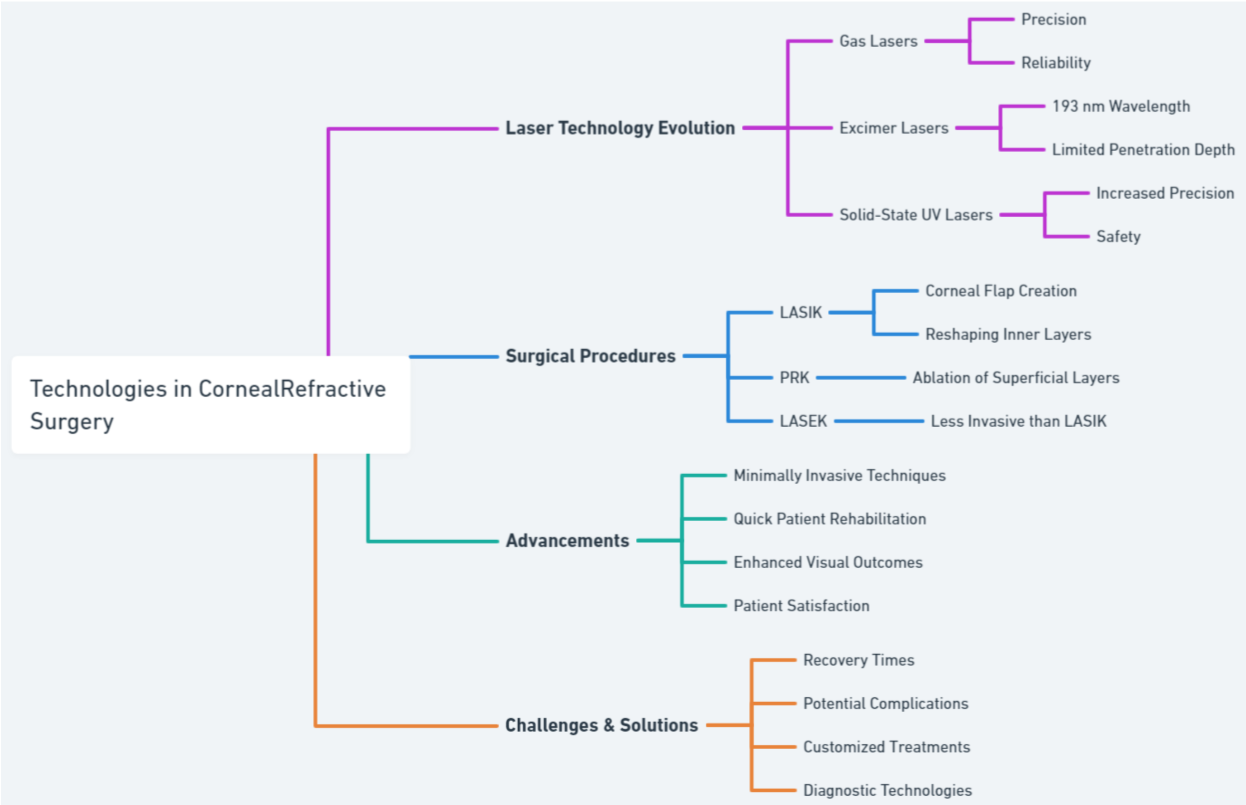

Fig. 3. Advancements in Corneal Refractive Surgery

3 | NEW GENERATION OF ABLATIVE SOLID-STATE LASERS

Based on the obtained information, it is evident that science is continuously advancing, with new technologies being developed every day. It is conceivable that Ablative Solid-State Lasers may emerge as successors to Solid-State Ultraviolet Lasers in refractive corneal surgery in the near future. This evolution would likely reflect ongoing improvements in precision, safety and the ability to tailor treatments to individual patient needs, all of which are central concerns in the development of ophthalmological surgical tools [15].

The study concludes that the new generation solid-state laser, AquariuZ, is effective and safe for use in LASIK surgeries. It has shown promising results in terms of visual acuity improvements and stability postsurgery without inducing significant higher-order aberrations. These findings suggest that with the latest technological advancements, solid-state lasers could potentially bridge the historical gap between themselves and excimer lasers in refractive surgery applications.

This article contributes to the ongoing development and evaluation of refractive surgery technologies, offering an alternative to excimer lasers with the potential benefits of improved safety, efficacy, and patient satisfaction.

None of the eyes treated lost lines of best-corrected visual acuity (BCVA) during the follow-up period. The results indicated that the AquariuZ solid-state laser system is safe, as there were no significant postoperative complications reported. All patients showed improvement in uncorrected visual acuity

(UDVA) and corrected distance visual acuity (CDVA) postsurgery. These improvements were maintained throughout the follow-up period. The study reported that the applied aspheric optimized profiles did not induce higher-order aberrations or spherical aberration in the operated eyes, which is crucial for maintaining the quality of vision post-surgery. While there was a slight refractive regression noted in some patients, the overall refractive outcomes were positive, with most patients achieving or nearing their targeted refractive goals [15].

4 | CONCLUSIONS

Advancements in corneal refractive surgery, especially with the introduction of solid-state ultraviolet lasers, have marked a significant leap forward in ophthalmology. These lasers have revolutionized how surgeries are performed, offering better precision, reduced risks, and quicker recovery times for patients. The evolution from traditional gas and excimer lasers to solid-state variants underscores a shift toward more effective and safer surgical practices. In particular, the precision and minimal thermal damage associated with these lasers have led to improved surgical outcomes, enhancing patient satisfaction and visual recovery.

However, while solid-state UV lasers present numerous advantages, there are still challenges to address, such as the high costs and the specialized training required for surgeons. These factors can limit accessibility, particularly in regions with fewer resources. Furthermore, despite the benefits, these technologies are not suitable for all patients, with factors such as age and corneal thickness playing significant roles in determining the candidacy for refractive surgery. Nonetheless, the ongoing research and development in this field suggest a promising future, with continuous improvements aimed at overcoming current limitations and expanding the scope of treatable conditions. The commitment to innovation in corneal refractive surgery is likely to yield even safer, more effective, and more accessible treatments for vision correction.

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Oleksandr Kapustynskyi, is an accomplished mechanical engineer and researcher with a diverse educational background. Currently is Research Fellow and Lecturer at Vilnius Gediminas Technical University, Faculty of Mechanics (Lithuania). In 2011 he obtained a Junior Specialists degree in Chemical and Petroleum Engineering from Berdychiv College of Industrial, Economics and Law, Ukraine. After continued his studies at the National Technical University of Ukraine "Kyiv Polytechnic Institute," where earned his Bachelor's degree (2014) and his Master's degree (2016) in Mechanical. In 2023 he obtained a Doctoral degree at the VilniusTECH Faculty of Mechanics (Lithuania). His research focuses on the mechanical and material engineering, laser technologies, and welding's.

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