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High–power Light–Curing Units commercially available: a qualitative systematic review

Universidade Fernando Pessoa
Faculdade de Ciências da Saúde

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Trabalho apresentado à Universidade Fernando Pessoa
como parte dos requisitos para obtenção do
grau de Mestre em Medicina Dentária sob a orientação
da Prof.ª Doutora Patrícia Manarte Monteiro

RESUMO

Objetivos: Esta revisão sistemática qualitativa analisa a evidência *in vivo* e *in vitro* de fotopolimerizadores-LED de alta-irradiância (≥2000 mW/cm^2) e identifica os dispositivos comercialmente disponíveis.

Desenvolvimento: Pesquisa na *PubMed* e *B-on*, por estratégia PRISMA; Critérios de inclusão: artigos *in vitro* e *in vivo* com fotopolimerizadores LED de alta irradiância (≥2000 mW/cm^2), idioma Inglês, publicados entre 2010 e 2020; Os fotopolimerizadores-LED alta-potência disponíveis foram identificados pela base de dados de expositores do Congresso da Ordem dos Médicos Dentistas 2019. Dos 1803 artigos selecionados, 18 foram incluídos (15-*in vitro* e 3-*in vivo*). Foram descritos 32 fotopolimerizadores-LED; maioritariamente têm irradiância compreendida entre 2000-3000mW/cm^2; FlashMaxP3™(CMS Dental, Dinamarca) apresentou a maior irradiância (6000mW/cm^2).

Conclusão: A evidência sobre fotopolimerizadores-LED de alta-potência e seu uso clínico é escassa. A investigação é escassa quanto ao uso inadequado, eventos adversos no complexo pulpo-dentinário/tecidos biológicos e efeitos colaterais nas taxas de sobrevivência clínica de materiais à base de resina.

Palavras-Chave: *"LED Dental Curing Lights", "Dental Equipment", "Polymerization", "Dental Resins"*

ABSTRACT

Aims: This qualitative systematic review describes the *in vivo* and *in vitro* evidence of high–power LED-Light-Curing Units (LED-LCU) and identifies those commercially available.

Development: PubMed and B-on were assessed using PRISMA strategy. Studies that respected criteria: *in vitro* and *in vivo* studies of high–power (≥2000 mW/cm^2) output LCUs, for dental resin-based-materials, English language, from 2010 to 2020, were included. High-power LED-LCUs available were identified by Exhibitor's database of 2019 Portuguese-Dental-Association Congress. From 1803 screened articles, 18 (15 *in vitro* and 3 *in vivo)* included; Thirty-two LED-LCUs described: most with outputs of 2000-3000 mW/cm^2; FlashMaxP3™ (CMS Dental, Denmark) highest output (6000 mW/cm^2).

Conclusion: Evidence showing that high–power LCUs are the best clinical option is still very scarce. There is still insufficient research regarding the inadequate use of those LCUs, the adverse events in dentin-pulp complex/biological tissues and, the side-effects on resin-based materials clinical survival rates and polymerization quality.

Keywords: "LED Dental Curing Lights", "Dental Equipment", "Polymerization", "Dental Resins"

DEDICATÓRIA

À minha mãe, por acreditar em mim mesmo quando eu duvido. Pelo amor e entrega incondicionais.

Aos meus avós de coração, pela paciência e carinho.

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LIST OF ABBREVIATIONS

BISGMA– Bisphenol A-glycidyl methacrylate

C– Celsius

CQ– Camphorquinone

J/cm^2– Joule per square centimeter

IFU– Instructions for use

LED– Light–emitting diode

LCU– Light–curing unit

mW/cm^2– Milliwatts per square centimeter

mm– Millimeters

nm– Nanometers

RBC– Resin–based composite

SDS– Safety data sheet

UDMA– Urethane dimethacrylate

I. INTRODUCTION

Light-curing units (LCU) and an efficient irradiation procedure is indispensable for clinical success, thus, being aware of this simple, perhaps important task is crucial. Clinicians have at their disposal an unprecedented variety of LCUs so, in order to make informed decisions, dentists need to consider if the device they are operating is emitting an optimal light quality. Light-emitting diode (LED)-LCUs were introduced in the late 1990s and became increasingly popular for curing resin-based filling, restorative and luting materials. Nowadays, they are a chosen alternative to other commercially available LCUs- quartz tungsten halogen devices, plasma arc curing lights and argon laser. First generation of LED-LCUs produced poor output, but the current third generation is capable of delivering higher radiant emittance in short exposure time. These enhanced devices also became polywave technology emitting multiple wavelengths bands (Jandt and Mills, 2013; Mohammed and Ario, 2015). Compact, lightweight, portable, battery powered and lifetime lasting are some of the features that make this type of unit clinician's widely predilection (Santini, 2010). However, it is important to obtain additional data on the performance of newly developed LEDs as they still present some adverse events. Not only deleterious effects on resin-based materials and consequent clinical failures but also potential consequences to the patient and clinician. Also, unit's limitations and resistance must be examined and taken into consideration.

The aim of this qualitative systematic review was to describe the current *in vivo* and *in vitro* evidence in the perspective of the latest short-curing time high-power curing lights. As well as to collect and identify commercially available LCUs used in dental offices.

1. Materials and methods

This systematic review is according to the guidelines of the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) selection process (Figure 1).The search was systematically performed in two distinct electronic databases: PubMed and B-on, in order to identify all *in vivo* and *in vitro* studies on high-power light-curing units. The terms used in each electronic source are listed in Table 1.
A total of 1803 articles were assessed. The last search in the databases was performed in March 2020. After screening the articles, all papers were imported into Mendeley desktop 1.19.4 software to remove duplicates.

Table 1. Search strategy used in each electronic database.

Database	Terms used	Filters
PubMed	#1 (LED Dental Curing Lights) OR (Curing Lights, Dental) OR (Curing Light, Dental) OR (Dental Curing Light) OR (Dental Curing Lights) OR (Light, Dental Curing) OR (Lights, Dental Curing) #2 (High-intensity) OR (high intensity) #3 Search #1 AND #2	-Studies from 2010 to 2020 -Articles written in the English language
B-on	"LED" AND "Light-curing unit" AND "high intensity"	

The articles were selected based on a pre-defined eligibility criteria. All titles and abstracts were checked to verify the inclusion criteria: *in vitro* and *in vivo* studies referring to LED-LCUs. Only studies that evaluated dental light-cured resin-based materials with high-power output devices were included. Consequently, articles reporting exclusively halogen, plasma-arc or argon-ion laser curing lights, light-cured materials polymerized with radiant emittance below 2000 mW/cm^2 or whose radiant emittance was not mentioned were not considered. Only papers written in the English language and published within the years 2010 to 2020 were contemplated for this review. After the full text of the previously selected articles was analyzed, only papers that fulfilled all the already mentioned eligibility criteria, were included. A total of 15 *in vitro* and 3 *in vivo* studies were reviewed.

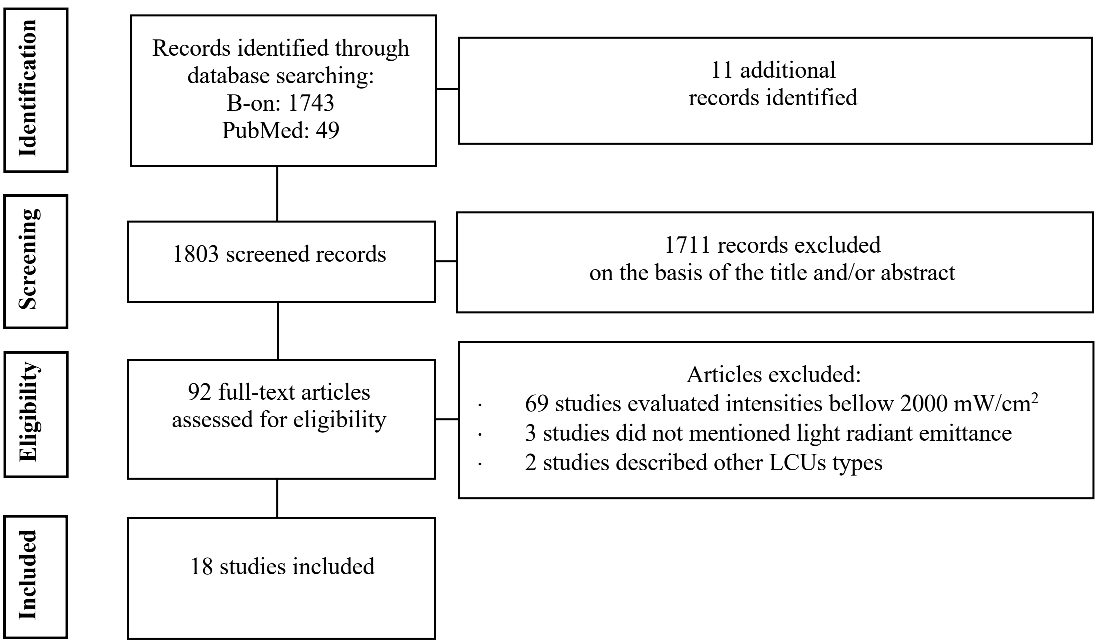

Figure 1. Review search strategy PRISMA flowchart.

To collect and identify commercially available LCUs used in dental offices an extensive hand-search was conducted. The last search was performed in April 2020.
Manufacturers commercially available in Portugal were identified through the Exhibitor's database of Portuguese Dental Association Congress, 2019 edition, Lisbon, Portugal (OMD, 2019). All manufacturers were assessed in order to identify all commercially available LED-LCUs with a claimed output ≥ 2000 mW/cm^2. Additionally, two dental material manufacturer's devices mentioned in the reviewed studies, that met the inclusion criteria, were retained for quality assessment.
Instructions for use (IFU) and Safety data Sheet (SDS) acquired directly from the LED-LCU manufacturer's online website were assessed to collect relevant data.

II. DEVELOPMENT

1. Dental materials light-curing and polymerization

1.1 Light Parameters

The quantity and quality of light generated by a LCU is highly dependent on the radiant emittance, exposure emission time, and spectral emission, respectively, but also on the interactions between these variables and their compatibility with the monomeric properties of the restorative material (Santini, 2010).

Dental composites are types of synthetic resins typically composed of three distinct phases: an organic matrix (polymerizable resin-based oligomer matrix, such as a bisphenol A-glycidyl methacrylate (BISGMA) or urethane dimethacrylate (UDMA)), an inorganic matrix (filler, such as silicon dioxide (silica)), and a coupling agent (such as silane, to enhance the bond between the two other components) (Cramer, Stansbury and Bowman, 2011).
The resin phase is composed of monomers that convert into a crosslinked polymer thru polymerization reaction. A critical feature of the light-cured composites and every resin-based dental material is its polymerization. The degree of polymerization is determined by the proportion of the remaining concentration of the double carbon bonds in a polymerized sample relative to the total number of double carbon bonds in the uncured material. The degree of conversion directly affects the chemical, physical, and mechanical properties of the composites and a higher degree of conversion indicates a greater amount of polymerization (Yılmaz, Bakkal and Zengin Kurt, 2020).
The following radiometric terms will be used in the present work.

Radiant emittance (expressed in units of mW/cm^2) describes the output from a curing light and therefore is the power emitted by the light source divided by the area of the light tip. While irradiance - also referred to as intensity or power density - is the power incident on a surface and describes what the resin receives (also expressed in units of mW/cm^2) (Price, Ferracane and Shortall, 2015). An irradiance level of 300 mW/cm^2 is considered by the International Organization for Standardization (ISO) as being enough to induce adequate polymerization of most light-cured resin-based materials (ISO 4049:2000 *cit. in* Santini 2010).

Spectral emission is designated by the wavelength range within the electromagnetic spectrum emitted. Efficient polymerization occurs when corresponding wavelengths match the maximum absorption of the material's photoinitiator system. Most of resin-based composite (RBC) contains two-components, the photo-initiator, generally a camphorquinone (CQ) which can absorb light directly, and a co-initiator, typically an amine, that does not absorb light but interacts with the activated photo-initiator to generate a reactive free radical and initiates resin-monomers polymerization (Brandt *et al.*, 2010; Pratap *et al.*, 2019).

Nonetheless, the total delivered optical energy depends on the exposure time. The emission of light to a given surface over time is called radiant exposure (expressed in units of J/cm^2) (Rueggeberg and Swift, 2013).
Current LED-LCUs may have multiple light modes with variation on light output emission and time protocol, allowing different radiant exposures.

1.2 LCU-related factors affecting the light output

The manufacturer-stated LCU irradiance value is rarely achieved. To ensure maximum efficiency, that is a higher degree of conversion of the organic monomers into polymer, the practitioner must be aware of the LCU device characteristics that may compromise the light transmitted (Zhou *et al.*, 2019).
Factors as the level of battery, use damage and, inadequate employment of disposable barriers and control methods to prevent cross-infection can affect the performance of the unit. To reduce and prevent the effect of the factors affecting the light output clinicians should periodically monitor that light output, track the level of battery, check the light tip for composite deposits and scratches and wisely use sterilization or disinfection control methods such as the autoclave, disinfectants and disposable infection control sleeves (McAndrew *et al.*, 2011; Pereira *et al.*, 2016).

2. Technology and evolution of LED light-curing units

According to the guideline MEDDEV 2.4/1 dental curing lights are Class I medical devices. This classification is in conformity with rule 12 of the European Directive 93/42/EEC (European Commission, 1993, 2010). LED is the acronym of Light Emitting Diode (Jandt *cit. in* Wilson, 2019).
As a result of the latest advancements in technology, gallium nitride blue light-emitting diodes curing units have been made available on the market and they were promising faster and deeper curing (Yılmaz, Bakkal and Zengin Kurt, 2020).

The first commercial LED-LCU became available in the late 1990s. First generation LED's radiant emittance ranged from 160 to 400 mW/cm^2 implicating less curing potential than conventional competitive types of LCUs. Later, in 2002, a second generation with a higher radiant emittance range of 500–1400 mW/cm^2 was introduced being able to reach values up to 1500 mW/cm^2 (Rahiotis *et al.*, 2010; Flury *et al.*, 2013). Those versions emitted a similar narrow spectra designed to match the absorption spectrum of CQ, the most common photoinitiator in resin-based dental materials (Jandt and Mills, 2013).
Around 2004, the advances in LED technology enabled the development of higher power LED-based systems: the third generation of LED curing units (Jandt and Mills, 2013). The radiant emittance levels were increased and devices are now capable of delivering values up to 5000 mW/cm^2 (Udomthanaporn, Nisalak and Sawaengkit, 2017).
Additionally, in order to address the mismatch between the emission spectrum and photoinitiators beside CQ, an additional emission peak was introduced in this LED-LCUs generation able to activate a wider range of photoinitiators. Those are equipped with multiple diodes, able to radiate both violet and blue light having an optimal spectral wavelength range within 400–500 nm (nanometers) (Jandt and Mills, 2013; Mohammed and Ario, 2015).
Newer LED curing units are being introduced advocating a fourth generation of LED-LCUs. Among several enhancements a wavelength scanning technology is the most significant improvement, allowing the clinician to select the appropriate output mode according to the material and clinical situation (Shortall *et al.*, 2012).

3. Results regarding High-power LED light-curing units

Literature is rather sparse regarding a definition for this term. Some authors reported that a LCU with radiant emittance >1500 mW/cm^2 is considered high-power (Shortall, Felix and Watts, 2015). Nevertheless, for this study — and according to Daugherty *et al.* (2018) — clinically acceptable radiant emittance values ≥ 2000 mW/cm^2 were considered.

3.1 High-power LED-LCUs commercially available

For each included LED-LCU the following data was recorded: manufacturer, radiant emittance and exposure time of high-power curing modes, estimated wavelength range, incorporated light meter, SDS, IFU, and brochure if available online.
If any information was missing, the manufacturers were contacted via e-mail to supply the missing data. When manufacturers failed to provide an answer, the respective information was mentioned as "Not Found".

Thirty-two marketed units with high level of radiant emittance were identified and their technical details are described in Table 2.
The following manufacturers BA International (Northampton, UK), Clarben (Madrid, Spain), Coltene Iberia S.L. (Madrid, Spain), DiaDent Europe (Almere, The Netherlands), Morita Europe (Dietzenbach, Germany) and MyRay (Bologna, Italy) commercialize one single high-power curing unit. On the other hand, Bader (Nigrán, Spain) developed distinct high-power curing lights. Aiming to incorporate particular features (i.e. broader emission spectrum, heads with different diameters or longer working time before cooling is needed) Acteon (Merignac, France), CMS Dental (Copenhagen, Denmark), DentLight (Dorset, UK), Ivoclar Vivadent Inc. (Schaan, Liechtenstein), Premium Plus UK Ltd (Dorset, UK), Ultradent Products Inc. (Utah, USA) and Woodpecker (Guangxi, China) offer different versions of their standard unit.

Optional curing modes are available in every curing unit, allowing the practitioner good control over the diverse clinical applications.
Dental manufacturers gave a variety of commercial names for the high-power modes, such as "High Power", "Boost", "Quick", "Xtra Power", "Turbo", and others — all consisting in a high radiant emittance and short-curing time light-setting. Most of the units had radiant emittance values between 2000–3000 mW/cm^2. The highest stated radiant emittance found was 6000 mW/cm^2, emitted by FlashMax P3™ (CMS Dental, Copenhagen Denmark).

Automatic exposure times are typically set, however adjustable time options are available in Be Light LED® (Bader, Nigrán, Spain), LED Light Curing® (Bader, Nigrán, Spain) and LED Clear® (Clarben, Madrid, Spain). These devices allow setting the desired time in the chosen work mode (i.e. 15 to 30 seconds).

Among the considered LED-LCUs seventeen are able to radiate multiple wavelengths compatible with different photoinitiators and, the additional fifteen are monowave units.

Maintenance and regular check of the light quality is essential. Eleven LCUs have light meters built into the charging base: MiniLED Standard®, MiniLED Supercharged® and MiniLED Ortho 2® (Acteon, Merignac, France), Bluephase Power Cure® (Ivoclar Vivadent Inc., Schaan, Liechtenstein) and T-LED (MyRay, Bologna, Italy) have an incorporated radiometer while Be Light LED® (Bader, Nigrán, Spain), D-Lux+® (DiaDent Europe, Almere, The Netherlands), C01-D™, C02-D™, C01-S™ and C02-S™ (Premium Plus UK Ltd, Dorset, UK) have light intensity sensors not specified by the manufacturers.

The light output from a curing unit can rarely be reliably measured by a commercial dental radiometer. Also, a single irradiance value cannot completely describe the output of a LCU. To overcome these limitations, calibrated spectrometer-based systems can be used. Since those equipments are not available in regular dental offices, manufacturers should provide accurate information about the distribution of the radiant emittance and spectral emission across the light tip in all available settings (Price, Ferracane and Shortall, 2015).

The searched units are cordless, battery-powered and include sleep mode to save battery life. Each one displays different handle designs, but all pledge a well-balanced combination of efficiency and comfort for both patient and clinician. Depending on the curing light selected patented features are available as *Navikey*, an intuitive control for simple operation in Ultimate Base 290 (Ba International, Northampton, UK) or *Polyvision technology* of Bluephase PowerCure® (Ivoclar Vivadent Inc., Schaan, Liechtenstein) that alerts the user for improper operation when movement of the hand piece during the curing procedure is detected.

Accessories such as interchangeable light tips of different configuration and various diameters are available.

LED-LCUs, SDA, IFU and link to brochure are presented in Table 3 (Annexes).

Table 2. High-power LED-LCUs commercially available and technical details: manufacturer, LED-LCU, radiant emittance and exposure time of high-power curing modes, estimated wavelength range, incorporated light meter.

Manufacturer	**LED-LCU** (Ref. number)	**High-power curing modes**	**Radiant emittance** (mW/cm^2)	**Exposure time** (seconds)	**Wavelenght range** (nm)	**Light meter built in**
ACTEON	**MINILED STANDARD®** (F02530)	**Fast**	2000	6 or 12	420-480	Yes
	MINILED SUPERCHARGED® (F05217)	**Fast-Cure**	2000 (7.5mm light tip) 3000 (5.5mm light tip)	3, 4, 5 or 10	420-480	Yes
	MINILED ORTHO 2® (F05220)	**Fast Cure**	3000	4, 8, 12 or 32	420-480	Yes
BA INTERNATIONAL	**ULTIMATE BASE290** (BA110200)	**Power Level 3** **Power Level 4**	2000 3000	1, 3 or 5 1, 3 or 5	380-500	No
BADER	**BE LIGHT LED®** (09070004)	**NF**	2000	15 to 30 (adjustable)	420-480	Yes
	LED LIGHT CURING® (090770008)	**NF**	2000	5 to 40 (adjustable)	420-480	No
	ONE LED LIGHT® (09070088)	**NF**	2300	1, 5 or 10	385-515	No
CLARBEN	**LED CLEAR®** (09-080)	**Bright Light**	2000	5 to 40 (adjustable)	420-480	No
CMS DENTAL	**FLASHMAX P3™** (100400)	**Green** **Orange** **Red**	5000 to 6000	1 or 3 1 or 3 (two activations with 0.5s pause) 1 or 3 (repetitive cycles with 0.5s pause)	440-480	No
	FLASHMAX P3 WIDE SPECTRUM™ (100403)	**Green** **Orange** **Red**	5000 to 6000	2 or 4 2 or 4 (two activations with 0.5s pause) 2 or 4 (repetitive cycles with 0.5s pause)	390-480	No
	FLASHMAX P3 ORTHO™ (NF)	**Green** **Orange** **Red**	5000 to 6000	1 or 3 1 or 3 (two activations with 0.5s pause) 1 or 3 (repetitive cycles with 0.5s pause)	440-480	No
COLTENE	**S.P.E.C. 3®** (60013942)	**3K** **Ortho**	3000 3000	1, 2 or 3 1, 2 or 3	430-490	No
DENTLIGHT	**FUSION 5™** (7800080)	**Pulse** **Plasma**	2000 4000	3, 5, 10, 20 or 60 3	420-490	No
	FUSION GRAND™ (7830060)	**Pulse** **Plasma**	2000 4000	3, 5, 10, 20 or 60 3	385-490	No
	FUSION PLUS™ (7820060)	**Pulse** **Plasma**	2000 4000	3, 5, 10, 20 or 60 3	385-490	No
DIADENT	**D-LUX+®** (4008-1110)	**Max Power**	2400	1, 2 or 3	385-515	Yes
IVOCLAR VIVADENT	**BLUEPHASE POWER CURE®** (667092)	**3sCure** **Turbo**	3000 2000	3 5	385-515	Yes
	BLUEPHASE STYLE 20i® (682110)	**Turbo**	2000	5	385-515	No
MORITA	**PENCURE 2000** (NF)	**High Power**	2000	2 or 3	380-430	No
MYRAY	**T-LED** (70140020)	**Standard** **Quick**	2400 (5mm light tip) 2200 (8mm light tip) 3780 (5mm light tip)	1, 2 or 3 1, 2 or 3	430-490	Yes
PREMIUM PLUS	**C01-DUAL RANGE™** (NF)	**Turbo** **3'+3'**	2000 2000	4 3 (two activations with 1s pause)	390-480	Yes
	C02-DUAL RANGE™ (NF)	**Turbo** **3'+3'**	2500 2000	3 3 (two activations with 1s pause)	390-480	Yes
	C01-SUPER POWER™ (NF)	**Turbo** **3'+3'**	2000 2000	4 3 (two activations with 1s pause)	440-480	Yes
	C02-SUPER POWER™ (NF)	**Turbo** **3'+3'**	2500 2000	3 3 (two activations with 1s pause)	440-480	Yes

Table 2. (cont.) High-power LED-LCUs commercially available and technical details: manufacturer, LED-LCU, radiant emittance and exposure time of High-power curing modes, estimated wavelength range, incorporated light meter.

Manufacturer	LED-LCU (Ref. number)	High-power curing modes	Radiant emittance (mW/cm²)	Exposure time (seconds)	Wavelenght range (nm)	Light meter built in
ULTRADENT	**VALO®** (5941)	**Xtra Power**	3200 (8mm light tip)	3	395-480	No
	VALO GRAND® (5972)	**Xtra Power**	3200 (12mm light tip)	3	385-515	No
	VALO ORTHO® (5942)	**Xtra Power** **Xtra Power Q**	3200 3200	1, 2 or 3 3 (five activations with 2s pause)	395-480	No
WOODPECKER	**B-CURE®** (NF)	**Ortho**	2000	3 or 5 (ten activations with 1s pause)	385-515	No
	B-CURE PLUS® (NF)	**Turbo**	2800 to 3000	1 or 3	385-515	No
	ILED® (NF)	**Turbo**	2300 to 2500	1 or 3	420-480	No
	ILED PLUS® (NF)	**Turbo**	2300 to 2500	1 or 3	385-515	No
	X-CURE® (NF)	**High**	2300 to 2500	1, 2 or 3	385-515	No
NF- Not found						

Thirteen SDS and IFU were not found online and were not available for analysis. Before operation, clinicians should verify data regarding the LCU handling, safety, efficiency, and maintenance.

3.2 Qualitative analysis on High-power LED-LCUs: *in vivo* and *in vitro* studies

To evaluate the performance of light curing units with radiant emittance ≥ 2000 mW/cm^2 eighteen studies were considered.

A total of fifteen *in vitro* studies (Annexes, Table 4) were reviewed.
Three studies aimed to evaluate temperature changes in the pulp exposed to high-power LED-LCUs (Park, Roulet and Heintze, 2010; Armellin *et al.*, 2016; Vinagre *et al.*, 2019). According to those authors' results, the temperature increase is closely related to the amount of radiant exposure rather than to the irradiance alone. The higher the radiant exposure, the more the pulp temperature increases. Therefore, a short and high radiant emittance, contrarily to a long exposure time, might be considered neither critical nor a potential damage to the pulp vitality.

Twelve studies investigated the effects on dental resin-based material's properties cured with high-power LED-LCUs. Three directly measured the degree of conversion (Flury *et al.*, 2013; Haenel *et al.*, 2015; Shimokawa *et al.*, 2017; Daugherty *et al.*, 2018), one assessed the depth of cure (Daugherty *et al.*, 2018), and seven analyzed microhardness values (Branchal *et al.*, 2015;

Gonulol, Ozer and Tunc, 2015; Haenel *et al.*, 2015; Watanabe *et al.*, 2015; Peutzfeldt, Lussi and Flury, 2016; Bilgic *et al.*, 2017; Shimokawa *et al.*, 2017). Other properties were evaluated, such as diametral tensile strength (Nurlatifah, Eriwati and Indrani, 2018), elastic modulus (Bilgic *et al.*, 2017), shear bond strength and adhesive remnant index (Udomthanaporn, Nisalak and Sawaengkit, 2017; Almeida, Martins and Martins, 2018). Results of those studies allow recognizing that the radiant exposure is more correlative to material properties than to the irradiance parameter itself.

Out of these twelve studies, six reported that high-intensities resulted in a similar outcome in comparison to lower irradiances, advocating its use with the advantage of shorter light curing times (Flury *et al.*, 2013; Branchal *et al.*, 2015; Watanabe *et al.*, 2015; Peutzfeldt, Lussi and Flury, 2016; Bilgic *et al.*, 2017). In the other six studies the authors concluded that a light curing protocol with lower irradiation and longer exposure outperforms all other combinations (Gonulol, Ozer and Tunc, 2015; Haenel *et al.*, 2015; Shimokawa *et al.*, 2017; Almeida, Martins and Martins, 2018; Daugherty *et al.*, 2018; Nurlatifah, Eriwati and Indrani, 2018).

A total of three *in vivo* studies (Annexes, Table 5) were assessed.

Runnacles *et al.* (2015) aimed to evaluate the temperature rise in anesthetized human pulp exposed to a high-power LED-LCU. Eighty volunteers with well-controlled health conditions requiring extraction of healthy, intact, non-carious, non-restored, fully erupted, upper right and left premolars were selected. The teeth were sequentially exposed to the following exposure modes: 10s in low intensity, 10 seconds in high-intensity, 60 seconds in high-intensity and 5 seconds in turbo intensity, in Bluephase 20i® (Ivoclar Vivadent Inc., Schaan, Liechtenstein). The temperature rise in pulp tissue, was measured inserting a type T thermocouple into the pulp chamber. Despite imposed limitations such as, local anesthesia that may have affected the heat dissipation and other clinical circumstances, as different remaining dentin or enamel thickness, under which composite restorations are placed, the authors concluded that exposing the tooth to a polywave LED-LCU developed a significant increase in pulp temperature in all evaluated exposure modes but, only the delivery of the high radiant exposure values might be potentially dangerous for the pulp.

Ward *et al*. (2015) evaluated the clinical performance of brackets bonded with a high-power LED-LCU. Thirty-four patients and a total of 680 brackets using a randomized split-mouth design were evaluated. Two different settings of VALO Ortho® (Ultradent Products Inc., Utah, USA) were used. In 17 participants the maxillary right and mandibular left quadrants were cured with 3200 mW/cm^2 setting during 6 seconds per tooth while the maxillary left and mandibular right quadrants were cured for 20 seconds with 1200 mW/cm^2. On the other 17 patients the quadrants were inverted. All participants were observed for a minimum period of 6 months. The authors concluded that 6 seconds curing time per tooth with a high-power curing light is sufficient to produce clinically adequate bond failure rates, that are comparable to brackets cured with a standard LED for 20 seconds.

Oz *et al*. (2016) also examined the clinical performance of brackets bonded with a high-power LED-LCU. Forty patients were included in the clinical part of this study. A split-mouth design was used. In Group 1, the adhesive was cured for 10 seconds with Elipar S10™ (3M Unitek, Monrovia, Calif) and in Group 2, for 3 seconds with VALO Ortho® (Ultradent Products Inc., Utah, USA). Bond failures during 12 months of orthodontic treatment were recorded. In-vitro performance of the brackets was also compared by bonding brackets to extracted premolars and using the same light units and curing times. The authors concluded that bracket bonding can be safely accomplished with the two LED-LCUs.

Although all studies were undertaken in ideal curing condition and the curing units in interest were used in maximum high-power mode, the results obtained were difficult to compare due to the different methodologies employed.

3.3 Advantages, challenges and possible adverse events

The advantage of introducing high-intensities in contemporary LED-LCUs was successful in reducing the chair-time (Flury *et al.*, 2013; Branchal *et al.*, 2015; Watanabe *et al.*, 2015; Peutzfeldt, Lussi and Flury, 2016; Bilgic *et al.*, 2017). So, it led to a dramatic reduction in curing time and to an increase in patient comfort (Yılmaz, Bakkal and Zengin Kurt, 2020).

However, some challenges need to be addressed and contextualized, in order to minimize or prevent possible adverse and side-events.
Consecutive and prolonged emissions induce significant and cumulative temperature rise that may lead to a potential damage of the dentin-pulp complex (Park, Roulet and Heintze, 2010; Armellin *et al.*, 2016; Vinagre *et al.*, 2019). Symptoms such as hyperalgesia, hypersensitivity and spontaneous pain, typical of acute pulpitis suggest this damage (Vinagre *et al.*, 2019).

Another situation that needs to be addressed is the deficient levels of polymerization as result of insufficient monomer-to-polymer conversion. Consequences include deterioration in chemical, physical, and mechanical material properties and subsequent increasing water absorption, marginal wear and microleakage, and susceptibility to discoloration and staining (Gonulol, Ozer and Tunc, 2015; Haenel *et al.*, 2015; Shimokawa *et al.*, 2017; Almeida, Martins and Martins, 2018; Daugherty *et al.*, 2018; Nurlatifah, Eriwati and Indrani, 2018). Also, decrease in biocompatibility, after all if not properly cured monomer elution and leaching out of components to the pulp or gingival tissues may occur (Shimokawa *et al.*, 2017).

The risk of heat build-up of the LCU is yet another issue (Branchal *et al.*, 2015). Some manufacturers limit maximum curing time, others allow consecutive exposure periods. When the light overheats, it's advisable to plug it into the charger to reset before it can be used again.

4. Discussion

The use of LED technology to polymerize dental resin-based materials offers practical advantages. These lightweight, portable and ergonomic devices provide an easier handling, long battery time, energy efficiency to operate for longer periods (before cooling is needed), and a lasting lifetime up to 10.000 hours (Eren and Tutkan, 2019).The latest high-power curing units incorporate the ideal features of the best LED-LCUs, and the most suggestive development is related to reducing chair-time.

Nevertheless, there are still problems to overcome.
Over-curing and longer exposures are dangerous to the biological vital pulp, and other tissues. According to Runnacles *et al*. (2015) delivering radiant exposure values > 80 J/cm^2 to the teeth, might induce pulp temperature rise above the acceptable threshold of 5.5ºC (Celsius), therefore, when applying high-power protocols and short-curing times, interval spans between each exposure are advisable to avoid consequences to pulp vitality and subsequent signs and symptoms development. As claimed by Rueggeberg *et al.* (2017) and Alasiri, Algarni and Alasiri (2019) other adverse events have been reported, as burning sensation on the surrounding soft tissues and ocular hazard, when high levels of blue light are emitted.

Furthermore, radiant exposure and spectral emission values of LCU, as claimed by the manufacturers, may not properly have a suitable correlation with the resin-based restorative material's higher degree of conversion and/or photo-initiators (Brandt *et al.*, 2010; Pratap *et al.*, 2019).

As it has already been identified, the output of LED-LCU can cause inadequate and inhomogeneous degree of conversion on the restorative material due to the introduction of multiple peak emission. Haenel *et al.* (2015) and Shimokawa *et al.* (2017) stated that the beam profile at the tip of dental LCUs is not uniform.

Also, it is still controversially discussed in the literature whether the use of the latest LCUs with very high radiant emittance values may actually require longer exposure than the values suggested by the manufacturer to properly cure restorative materials (Rueggeberg and Swift, 2013). The concept of exposure reciprocity assumes that when applying the same radiant exposure, the degree of conversion will be the same, regardless of the irradiance level or time of exposure. While some authors question this statement and assume that such relationship cannot be established when using high-power LCUs (Gonulol, Ozer and Tunc, 2015; Haenel *et al.*, 2015; Shimokawa *et al.*, 2017; Almeida, Martins and Martins, 2018; Daugherty *et al.*, 2018; Nurlatifah, Eriwati and Indrani, 2018), others, on the other hand, agree on the potential of these lights in reducing irradiation time without a significant loss of mechanical properties (Flury *et al.*, 2013; Branchal *et al.*, 2015; Watanabe *et al.*, 2015; Peutzfeldt, Lussi and Flury, 2016; Bilgic *et al.*, 2017).

Since it is complex and difficult to predict the effects of a specific curing light and its possible consequences on a restorative material, manufacturers specific recommendations must be seen as helpful directives however, susceptible to adjustments (Rueggeberg and Swift, 2013; Shimokawa *et al.*, 2016).

Six commercialized high-power LED-LCUs were tested in the reviewed studies. VALO® and VALO Ortho® (Ultradent Products Inc., Utah, USA), Flashmax P3™ (CMS Dental, Copenhagen Denmark), S.P.E.C.3® (Coltene Iberia S.L., Madrid, Spain), Fusion™ (DentLight, Dorset, UK), Pencure 2000 (Morita Europe, Dietzenbach, Germany) were tested *in vitro*. Only VALO Ortho® (Ultradent Products Inc., Utah, USA) performance was evaluated *in vivo.*

Although no particular LCU can be universally applied in all restorative procedures for a given time with predictably deliver optimal polymerization results, at the moment, VALO® (Ultradent Products Inc., Utah, USA) evidence showed an optimum combination of features and performance among the high-power curing lights.

A recent survey study identified specific knowledge gaps among Norwegian dentists with regard to curing lights and use of personal protection; those authors reported that today's dependence on technology in dentistry implies that the operator must be proficient in essential technical specifications and safe use of devices and instruments routinely applied in dental treatments (Kopperud *et al.*, 2017). Nevertheless dentist's awareness on technical features of their LCUs, practical use and safety is unsatisfactory nowadays (Santini and Turner, 2011; Kopperud *et al.*, 2017).

Also, there is a lack of perception on the need for monitoring and regular checking of the LED-LCU that are daily used in dental offices. Surveys of LCUs used in dental offices worldwide show that many deliver inadequate light output (Al Shaafi, Maawadh and Al Qahtani, 2011; Maghaireh, Alzraikat and Taha, 2013; Ernst *et al.*, 2018; Eren and Tutkan, 2019).

Thus, it is relevant, and therefore required, to improve the general knowledge level of dental clinicians regarding the use and general management of high-power LED-LCUs. Also, there is the need to increase evidence and research regarding the adverse events associated, or not, with the use of different high-power LED-LCU, from different manufacturers.

III. CONCLUSION

According to the purposes defined for this qualitative review and the described high-power LED-LCUs commercially available for direct resin-based restorative materials, it was possible to state the following conclusions:

– Fifteen *in vitro* studies were reviewed; three evaluated the temperature changes in the pulp exposed to high-power LED-LCUs, twelve investigated the effects on dental resin-based material's properties cured with high-power LED-LCUs. Reports suggest that the temperature increase and material properties are more closely related to the amount of radiant exposure rather than to the irradiance parameter itself.

– Only three *in vivo* studies were found and assessed; just one, evaluated the temperature rise in anesthetized human pulp exposed to a high-power LED-LCU, and two registered the clinical performance (bond failure rate) of bonded brackets, using just one high-power LED-LCU or comparing the use of a high-power LED-LCU to a standard LED-LCU, respectively. The use of polywave and/or high radiant exposure values can clinically damage the pulp. Shorter time exposures with a high-power LED unit can produce clinically adequate bond failure rates, and those results are comparable to bonded brackets cured with a standard LED for 20 seconds.

– Only six commercialized high-power LED-LCUs were tested in the reviewed studies: VALO and VALO Ortho® (Ultradent Products Inc., Utah, USA), Flashmax P3™ (CMS Dental, Copenhagen Denmark), S.P.E.C.3® (Coltene, Iberia S.L., Madrid, Spain), Fusion™ (DentLight, Dorset, UK), Pencure 2000 (Morita Europe, Dietzenbach, Germany) were tested *in vitro*. Only one LCU, VALO Ortho® (Ultradent Products Inc., Utah, USA), was studied *in vivo.*

– Thirty-two marketed units with high level of radiant emittance (≥ 2000mW/cm^2 and ≤ 6000 mW/cm^2) were identified, and their SDS and technical details collected. Optional curing modes are available in every curing unit such as, “High Power”, “Boost”, “Quick”, “Xtra Power”, “Turbo”, and others - all consisting in a high radiant emittance and short-curing time light-setting. Most of the units had radiant emittance values between 2000-3000 mW/cm^2. The highest stated radiant emittance found was 6000 mW/cm^2, emitted by FlashMax P3™ (CMS Dental, Copenhagen Denmark).

– Seventeen LED-LCU are able to radiate multiple wavelengths compatible with different photoinitiators and, the additional fifteen are monowave units.

– LCUs maintenance and regular checks are essential. Eleven LCUs have light meters built into the charging base; five of those LCUs have an incorporated radiometer, the other six have other light intensity sensors not specified by the manufacturers. To overcome limitations such as reliability of LED-LCU light output measures, a calibrated spectrometer-based systems is recommended for periodic monitoring. Since those equipment’s are not available in regular dental offices, manufacturers should provide accurate information about the distribution of the radiant emittance and spectral emission across the light tip in all available settings.

Much is still left to learn about the complex interactions between all light curing parameters. It is still being debated whether high radiant emittance results in a similar outcome in comparison to lower radiant emittance but with longer time exposures or if, it outperforms all other combinations. There is a lack of *in vivo* evidence both on the adverse events in dentin-pulp complex and biological surrounding tissues and the side-effects on clinical survival rates of resin-based materials associated to the degree of conversion/polymerization quality, generated by inadequate use of high-power and short time exposures LCUs.

The clinical-based evidence showing that high-power lights and faster curing times are the right choice and the best clinical option is still very scarce. It remains uncertain whether the radiant emittance of modern LED-LCUs has already reached its saturation level which reinforces the need for additional and further studies on this field.

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V. ANNEXES

Table 3. High-power LED-LCUs commercially available and technical details: manufacturer, LED-LCU, SDS, IFU, and link to brochure.

Manufacturer	LED-LCU (Ref. number)	Safety data and Instructions for use	LINK to Brochure
ACTEON	**MINILED STANDARD®** (F02530)	Available at <https://www.acteongroup.com/es/uploads/media/default/0001/01/444188825e19cff843cf686925b79f3efb247df5.pdf> (Accessed in 19/02/2020)	https://www.acteongroup.com/us/uploads/media/default/0001/02/c78ead949c280a70a5acb0de76f8d0d386d9783f.pdf (Accessed in 21/04/2020)
	MINILED SUPERCHARGED® (F05217)	Available at <https://www.acteongroup.com/es/uploads/media/default/0001/01/45de84dd04184927973481ea27a32bd5b126e089.pdf> (Accessed in 19/02/2020)	https://www.acteongroup.com/us/uploads/media/default/0001/02/c78ead949c280a70a5acb0de76f8d0d386d9783f.pdf (Accessed in 21/04/2020)
	MINILED ORTHO 2® (F05220)	Available at <https:// https://www.acteongroup.com/us/uploads/media/default/0001/01/d57b6f0c62b68188932a263f44a400fe9b383d76.pdf> (Accessed in 19/02/2020)	https://www.acteongroup.com/us/uploads/media/default/0001/02/c78ead949c280a70a5acb0de76f8d0d386d9783f.pdf (Accessed in 21/04/2020)
BA INTERNATIONAL	**ULTIMATE BASE290** (BA110200)	Available at <https://www.bainternational.com/pub/media/kuki/download/50/BASE290-IFU-FINAL.pdf> (Accessed in 20/02/2020).	NF https://www.bainternational.com/ba110200.html (Accessed in 21/04/2020)
BADER	**BE LIGHT LED®** (09070004)	Available at <http://www.bader.es/gb/index.php?controller=attachment&id_attachment=69> (Accessed in 21/04/2020)	http://www.bader.es/gb/index.php?controller=attachment&id_attachment=26 (Accessed in 21/04/2020)
	LED LIGHT CURING® (090770008)	Available at <http://www.bader.es/gb/index.php?controller=attachment&id_attachment=70> (Accessed in 21/04/2020)	NF http://www.bader.es/gb/clinic-equipment/587-led-light-curing-lamp.html?search_query=one+light&results=35 (Accessed in 21/04/2020)
	ONE LED LIGHT® (09070088)	NF http://www.bader.es/gb/clinic-equipment/1243-one-led-light-bader.html?search_query=one+light&results=35 (Accessed in 21/04/2020)	NF http://www.bader.es/gb/clinic-equipment/1243-one-led-light-bader.html?search_query=one+light&results=35 (Accessed in 21/04/2020)
CLARBEN	**LED CLEAR®** (09-080)	Available at <https://clarben.com/_files/200000330-3a62b3b5bd/FT-SGC15.01%20LAMPARA%20LED%20CLEAR.pdf> (Accessed in 21/04/2020)	NF https://www.clarben.com/pt/aparelho-clinico/ (Accessed in 21/04/2020)
CMS DENTAL	**FLASHMAX P3™** (100400)	NF https://www.cmsdental.com/?id=422&c=Technic%20Flash&ulang=2 (Accessed in 21/04/2020)	http://www.cmsdental.com/gfx/pdf/FP3_Brochure_PRINT.pdf (Accessed in 21/04/2020)
	FLASHMAX P3 WIDE SPECTRUM™ (100403)	NF https://www.cmsdental.com/?id=422&c=Technic%20Flash&ulang=2 (Accessed in 21/04/2020)	http://www.cmsdental.com/gfx/pdf/FP3_Brochure_PRINT.pdf (Accessed in 21/04/2020)
	FLASHMAX P3 ORTHO™ (NF)	NF https://www.cmsdental.com/?id=422&c=Technic%20Flash&ulang=2 (Accessed in 21/04/2020)	http://www.cmsdental.com/gfx/pdf/FP3_Brochure_PRINT.pdf (Accessed in 21/04/2020)
COLTENE	**S.P.E.C. 3®** (60013942)	Available at <https://www.coltene.com/pim/DOC/IFU/docifu40001378g-spec3-ifu-multisallaindv1.pdf> (Accessed in 18/11/2019)	https://www.coltene.com/pim/DOC/BRO/docbro60018424-11-15-brochure-spec3-ensenaindv1.pdf (Accessed in 19/04/2020)
DENTLIGHT	**FUSION 5™** (7800080)	Available at <http://www.dentlight.com/////////////wp-content/uploads/2019/07/FUSION5-Platform-IFU.pdf> (Accessed in 22/04/2020)	http://www.dentlight.com/////////////wp-content/uploads/2019/07/fusion-5-platform-brochure.pdf (Accessed in 22/04/2020)
	FUSION GRAND™ (7830060)	Available at <http://www.dentlight.com/////////////wp-content/uploads/2019/07/FUSION5-Platform-IFU.pdf> (Accessed in 22/04/2020)	http://www.dentlight.com/////////////wp-content/uploads/2019/07/fusion-5-platform-brochure.pdf (Accessed in 22/04/2020)
	FUSION PLUS™ (7820060)	Available at <http://www.dentlight.com/////////////wp-content/uploads/2019/07/FUSION5-Platform-IFU.pdf> (Accessed in 22/04/2020)	http://www.dentlight.com/////////////wp-content/uploads/2019/07/fusion-5-platform-brochure.pdf (Accessed in 22/04/2020)
DIADENT	**D-LUX+®** (4008-1110)	NF http://www.diadenteurope.com/producten/small-equipment/d-luxplus-cordless-curing-light (Accessed in 22/04/2020)	http://www.diadenteurope.com/media/1303/d-lux-plus-brochure.pdf (Accessed in 21/02/2020)
IVOCLAR VIVADENT	**BLUEPHASE POWER CURE®** (667092)	Available at <http://downloads.ivoclarvivadent.com/zoolu-website/media/document/46806/Bluephase+PowerCure> (Accessed in 20/11/2019)	https://www.ivoclarvivadent.com/zoolu-website/media/document/46802/Bluephase+PowerCure (Accessed in 22/04/2020)
	BLUEPHASE STYLE 20i® (682110)	Available at <http://downloads.ivoclarvivadent.com/zoolu-website/media/document/39483/Bluephase+Style+20i+-+en%2C+de%2C+fr%2C+it%2C+es%2C+pt> (Accessed in 18/11/2019)	https://www.ivoclarvivadent.com/zoolu-website/media/document/33153/Bluephase+Style+Line (Accessed in 22/04/2020)
MORITA	**PENCURE 2000** (NF)	NF https://www.jmoritaeurope.de/en/products/handpieces-and-instruments/curing-light/pencure/ (Accessed in 22/04/2020)	https://www.jmoritaeurope.de/cms/files/pencure_2000_en_screen.pdf?download=1 (Accessed in 18/11/2019)
MYRAY	**T-LED** (70140020)	NF https://www.myray.it/en/myray/ (Accessed in 22/04/2020)	http://www.sternweber.cz/wp-content//2015/04/T-Led_MyRay_flyer12_GB.pdf (Accessed in 21/02/2020)
PREMIUM PLUS	**C01-DUAL RANGE™** (NF)	NF https://www.premiumplusuk.com/product/c01-d-led-curing-light-with-fibre-optic-light-guide/ (Accessed in 15/11/2019)	NF https://www.premiumplusuk.com/product/c01-d-led-curing-light-with-fibre-optic-light-guide/ (Accessed in 15/11/2019)
	C02-DUAL RANGE™ (NF)	NF https://www.premiumplusuk.com/product/c02-d-led-curing-light-90-right-angle-direct-light-source-head/ (Accessed in 15/11/2019)	NF https://www.premiumplusuk.com/product/c02-d-led-curing-light-90-right-angle-direct-light-source-head/ (Accessed in 15/11/2019)
	C01-SUPER POWER™ (NF)	NF https://www.premiumplusuk.com/product/c01-s-led-curing-light-with-fibre-optic-light-guide/ (Accessed in 15/11/2019)	NF https://www.premiumplusuk.com/product/c01-s-led-curing-light-with-fibre-optic-light-guide/ (Accessed in 15/11/2019)

Table 3. (cont.) High-power LED-LCUs commercially available and technical details: manufacturer, LED-LCU, SDS, IFU, and link to brochure.

Manufacturer	**LED-LCU** (Ref. number)	**Safety data and Instructions for use**	**LINK to Brochure**
PREMIUM PLUS	**C02-SUPER POWER™** (NF)	NF https://www.premiumplusuk.com/product/c02-s-led-curing-light-90-right-angle-direct-light-source-head/ (Accessed in 15/11/2019)	NF https://www.premiumplusuk.com/product/c02-s-led-curing-light-90-right-angle-direct-light-source-head/ (Accessed in 15/11/2019)
ULTRADENT	**VALO®** (5941)	Available at <https://downloads.ctfassets.net/wfptrcrbtkd0/d9d85c84-455f-48e9-89c2-a5dcf5a77c76/52249689369e5d494f8559bef7ed0dbe/VALO_Cordless.pdf> (Accessed in 20/11/2019)	NF https://www.ultradent.com/products/procedures/restorative/class-I-II-III-IV-composite-restoration/curing-lights/valo-cordless (Accessed in 23/04/2020)
	VALO GRAND® (5972)	Available at <https://www.ultradent.com/Resources/DownloadSds?url=000%2F749%2F549%2Fagile74954940.pdf&filename=VALO®%20Cordless%20%26%20VALO®%20Ortho%20Cordless%20Rechargeable%20Battery%20SDS%20%28English%29> (Accessed in 23/04/2020) and at <https://downloads.ctfassets.net/wfptrcrbtkd0/5b8bca4d-8dbb-422c-9b6a-503037b12e88/d909a348d5d9c14f2543d144ec7f2eaf/VALO-Grand.pdf> (Accessed in 20/11/2019)	NF https://www.ultradent.com/products/procedures/restorative/class-I-II-III-IV-composite-restoration/curing-lights/valo-grand (Accessed in 23/04/2020)
	VALO ORTHO® (5942)	Available at <https://www.ultradent.com/Resources/DownloadSds?url=000%2F749%2F549%2Fagile74954940.pdf&filename=VALO®%20Cordless%20%26%20VALO®%20Ortho%20Cordless%20Rechargeable%20Battery%20SDS%20%28English%29 (Accessed in 23/04/2020) and at <https://downloads.ctfassets.net/wfptrcrbtkd0/c6d0c2b1-6a80-4bed-a2e2-5a214669d2e1/2954f126e5b59055bf32ec949b1313bd/VALO_Ortho_Cordless.pdf> (Accessed in 23/04/2020)	NF https://www.ultradent.com/products/procedures/restorative/class-I-II-III-IV-composite-restoration/curing-lights/valo-ortho-cordless?sku=5942- (Accessed in 23/04/2020)
WOODPECKER	**B-CURE®** (NF)	NF http://www.glwoodpecker.com/index.php?m=content&c=index&a=show&catid=36&id=197 (Accessed in 23/04/2020)	NF http://www.glwoodpecker.com/index.php?m=content&c=index&a=show&catid=36&id=197 (Accessed in 23/04/2020)
	B-CURE PLUS® (NF)	NF http://www.glwoodpecker.com/index.php?m=content&c=index&a=show&catid=36&id=195 (Accessed in 23/04/2020)	NF http://www.glwoodpecker.com/index.php?m=content&c=index&a=show&catid=36&id=195 (Accessed in 23/04/2020)
	ILED® (NF)	Available at <http://www.glwoodpecker.com/shuomingshu/iLedyingwen.pdf> (Accessed in 23/04/2020)	NF http://www.glwoodpecker.com/index.php?m=content&c=index&a=show&catid=36&id=44 (Accessed in 23/04/2020)
	ILED PLUS® (NF)	Available at <http://www.glwoodpecker.com/uploadfile/2019/0428/20190428095242495.pdf> (Accessed in 23/04/2020)	NF http://www.glwoodpecker.com/index.php?m=content&c=index&a=show&catid=36&id=159 (Accessed in 23/04/2020)
	X-CURE® (NF)	Available at <http://www.glwoodpecker.com/uploadfile/2019/1021/20191021104758956.pdf> (Accessed in 23/04/2020)	NF http://www.glwoodpecker.com/index.php?m=content&c=index&a=show&catid=36&id=45 (Accessed in 23/04/2020)
NF- Not found			

Table 4. Performance of High-power LED-LCUs- *in vitro* evidence.

Study (Author, Year)	**Objective**	**Materials and Methods**	**Results**	**Conclusion**
(Park, Roulet and Heintze, 2010)	Examine the effect of **curing lights with different light intensities** on the increase and subsequent decrease in pulpal temperature during and after the light curing process.	A maxillary premolar was light-cured using four LCUs: Astralis 10 (Ivoclar Vivadent, Schaan, Liechtenstein) (1200 mW/cm^2) activated for 30 seconds and Bluephase 16i (Ivoclar Vivadent, Schaan, Liechtenstein) (1600 mW/cm^2) and two experimental LED curing lights (**$LED_{exp2000}$, $LED_{exp3000}$**, Ivoclar Vivadent, Schaan, Liechtenstein) (**2000 mW/cm^2** and **3000 mW/cm^2**), activated for 60 seconds.	The intrapulpal temperature increased more than 5ºC when the exposure time was more than 10 seconds with $LED_{exp2000}$ and $LED_{exp3000}$. It was noticed that although the maximum intrapulpal temperature produced by **$LED_{exp3000}$** was higher than **$LED_{exp2000}$** the disparity was not pronounced considering that the difference in power density between the two was approximately 1000 mW/cm^2.	Disparity in the temperature increase during the light-curing process between LCUs with different power densities was observed. A large increase would occur with LCUs with high-power density.
(Flury *et al.*, 2013)	Measure the degree of conversion of five dual-curing resin cements exposed to different curing modes with a second and a **third-generation LED curing unit.**	Light curing was performed with Elipar Freelight 2 (3M ESPE, Seefeld, Germany) in Standard mode (1200 mW/cm^2) and **VALO** (Ultradent, UT, USA) in High Power mode (1400 mW/cm^2) and **Xtra Power mode** (3200 mW/cm^2).	Light curing the five resin cements with a higher irradiance did not result in significantly higher degree of conversion.	The higher irradiances of the third-generation LED curing unit resulted in similar degree of conversion compared to the second-generation one, but with the advantage of shorter curing times.
(Haenel *et al.*, 2015)	Determine the irradiance distribution of **two light curing units** and its influence on the local mechanical properties of a RBC.	Composite samples were irradiated for 5, 20 and 80 seconds using **Bluephase® 20i** (Ivoclar Vivadent, Schaan, Liechtenstein) in Low (650 mW/cm^2) or **Turbo mode (2000 mW/cm^2)** and Celalux® 2 (VOCO, Cuxhaven, Germany) with variable irradiance (1000-1500 mW/cm^2), depending on the light tip.	The irradiance distribution affected the hardness distribution across the surface of the specimens.	The hardness distribution reflects the irradiance distribution of each LCU. Irradiance level and light exposure time do not affect the pattern of the hardness distribution, only the hardness level.
(Branchal *et al.*, 2015)	Determine if increasing recommended short curing times three **high-power LED curing lights would** adequately polymerize sealant materials.	Three sealants (opaque-unfilled, opaque-filled, and clear-filled) were light cured by three LED LCUs: **VALO** (Ultradent, Utah, USA) (**3200 mW/cm^2** for 3 seconds), **Fusion** (DentLight Inc., Texas, USA) (**2700 mW/cm^2 for** 5 seconds), **SmartLite Max** (Dentsply International, York, Pa., USA) (2805 mW/cm^2 for 10 seconds), They were tested doubling or tripling the exposure time. A halogen light-curing unit (XL3000, 3M ESPE, Minn, USA) was used as control.	Opaque-filled and clear-filled sealants hardness values polymerized by VALO at 6 or 9 seconds were statistically equivalent to or better than polymerized by the halogen light-curing unit at a depth of 1.5 mm. Opaque-unfilled sealant values, however, were lower beyond the sealant surface. Fusion at 10 seconds did not adequately cure the three sealants beyond 1 mm. SmartLite at 15 seconds did not adequately cure the sealants beyond 0.5 mm.	Among the high-intensity LED units tested, only VALO properly cured opaque-filled and clear-filled sealants at 1.5 mm depth.

Table 5. (cont.) Performance of High-power LED LCUs- *in vitro* evidence.

Study (Author, Year)	**Objective**	**Materials and Methods**	**Results**	**Conclusion**
(Gonulol, Ozer and Tunc, 2015)	Investigate the consequences of **different modes of a third-generation LCU** on the microhardness of restorative materials.	A microhybrid composite resin, a giomer-based composite resin, a compomer and a resin-modified glass ionomer cement were polymerized with different modes (1200 mW/cm^2, 1400 mW/cm^2 and **3200 mW/cm**^{2}) of **VALO** (Ultradent, MO, USA) and with a second-generation LCU: Elipar S10 (3M ESPE, MN, USA), used as control.	VALO used in Extra power mode for 6 seconds may not achieve sufficient polymerization of restorative material. However, VALO used in High-power mode for 12 seconds achieved microhardness values similar to those obtained with the VALO in Standard mode and Elipar S10.	The high-power mode of the VALO can be recommended for clinical applications as it can shorten the time required to adequately polymerize RBC.
(Watanabe *et al.*, 2015)	Evaluate the ability of **high-intensity LED** and other curing units to polymerize dual-cured resin cement through ceramic material.	A halogen curing unit: Jetlite 3000 (Morita, Tokyo, Japan), a second-generation LED LCU: Demi (Kerr, CA, USA), and two high-intensity LED curing units: **PenCure 2000** (Morita, Tokyo, Japan) (**2000 mW/cm**^{2}) and **VALO** (Ultradent, UT, USA) (**3200 mW/cm**^{2}) were tested.	In general, the Knoop Hardness Numbers decreased with increasing plate thickness and increased as the irradiation time was extended.	High-intensity LED units require a shorter irradiation period than halogen and second-generation LED curing units to obtain Knoop Hardness Numbers similar to those observed during direct irradiation.
(Armellin *et al.*, 2016)	Assess thermal changes on tooth structures exposed to **two different LED curing units**.	Two LED lamps were selected and tested: **VALO** (Ultradent, UT, USA) (1000 mW/cm^2 for 20 seconds or **3200 mW/cm**^{2} for 3 seconds) and Starlight PRO (Mectron, Carasco, Italy) (1000 mW/cm^2 for 20 seconds).	Overall thermal change was proportional to the exposure time. Light intensity of 3200 mW/cm^2 for 3 seconds resulted in lower elevations of temperature compared to a prolonged exposure of 20 seconds, despite the lower power.	Intrapulpal temperature increase during composite photocuring in related not only to the energy from the light unit, but also to the time application.
(Peutzfeldt, Lussi and Flury, 2016)	Study the impact of **light curing at high irradiances** on the micromechanical properties of resin cements.	Three dual-curing resin cements and a flowable resin composite were light-cured with **VALO** (Ultradent, UT, USA) in Standard mode, High power mode or **Xtra power mode (3200 mW/cm**^{2}**)**. Distinct exposure times were set to obtain two or three levels of radiant exposure, in each light-curing mode.	Doubling the radiant exposure, by doubling the exposure period in each mode, generally led to significant increases in the micromechanical properties, not impacting however all four materials similarly.	The irradiation protocol significantly influences micromechanical properties of dual curing resin cements due to variation of exposure time, indicating that high-irradiance light-curing has no detrimental effect on polymerization of resin-based materials.
(Udomthanaporn, Nisalak and Sawaengkit, 2017)	Evaluate adhesion of orthodontic brackets polymerized by **high-intensity LED curing units** at different intensities and curing times.	The adhesives were polymerized with Bluephase (Ivoclar Vivadent Inc., USA) (1200 mW/cm^2 for 20 seconds), **VALO** (Ultradent, UT, USA) (**3200 mW/cm**^{2} for 6 seconds) and **FlashMax P3** (CMS Dental, Copenhagen, Denmark) (**4000-6000 mW/cm**^{2} for 3 seconds).	Although Flashmax P3 had the highest light intensity, the shear bond strength was the lowest among the other LCUs. The mean shear bond strength of VALO at 6 seconds was not significantly different from Bluephase at 20 seconds.	VALO is a valid option to reduce working time.

Table 6. (cont.) Performance of High-power LED LCUs- *in vitro* evidence.

Study (Author, Year)	Objective	Materials and Methods	Results	Conclusion
(Bilgic *et al.*, 2017)	Compare the hardness and elastic modulus of orthodontic adhesives cured with third generation **LED curing units**.	Standardized samples of orthodontic adhesives were cured 3 seconds with **VALO Ortho** (Ultradent, Utah, USA) (**3200 mW/cm²**) and VALO (Ultradent, Utah, USA) (1400 mW/cm²).	Adhesives cured with VALO Ortho resulted in higher properties' values in comparison with VALO.	Reducing irradiation time in High-intensity LED curing units can provide satisfactory polymerization without adverse effects on mechanical properties of materials.
(Shimokawa *et al.*, 2017)	Examined the influence of different emission spectra **LCUs delivering the same radiant exposures** on the polymerization and light transmission of four RBC.	Two prototype LCUs either single-peak or broad-spectrum were used either in standard (1200 mW/cm²) or **high irradiance (3600 mW/cm²)** settings.	Although similar radiant exposures were delivered the degree of conversion and microhardness results varied according to the RBC. The RBC that included alternative photoinitiators had greater values with single-peak blue lights compared to broad-spectrum lights.	The emission spectrum and irradiance level influence the polymerization of RBC.
(Daugherty *et al.*, 2018)	Investigate the **effect of high-irradiance light-curing units** on the depth of cure and degree of polymerization of bulk-fill composites.	The composites were cured using two high-irradiance LCUs: **Flashmax-P3** (CMS Dental, Copenhagen, Denmark) (**5000-6000 mW/cm²) a**nd **S.P.E.C.3** (Coltene, OH, USA) (**3000-3500 mW/cm²**). Also, a conventional LCU was used: Paradigm (3M ESPE, MN, USA). Time exposures applied were of 3 or 9 seconds, 3 or 20 seconds, and 10 or 20 seconds, respectively.	All composites failed to satisfy ISO-4049 with the high-irradiance LCU with 3 seconds exposures. Standard irradiance and 20 seconds exposures outperform all other combinations.	Bulk-fill composites cured with high-irradiance and short exposure time may not provide adequate depth of cure and degree of polymerization, which can lead to undesirable clinical properties.
(Almeida, Martins and Martins, 2018)	Assess the effects of reducing the curing time of a **high-power LED unit** on bonding of metal brackets.	Human premolars were cured with **VALO Cordless** (Ultradent, UT, USA), in **Xtra curing mode** (**3200mW/cm²**).	Time significantly affected shear bond strength (6 seconds resulted in higher values in comparison to 3 seconds curing) but not the amount of adhesive remnant.	Reducing light-curing time lead to significantly lower mean values of shear bond strength, even with the use of a high-intensity LED unit.
(Nurlatifah, Eriwati and Indrani, 2018)	Assess the **influence of the curing time of a LED curing unit** on the diametral tensile strength of packable composite resin.	Specimens were cured with an ultra-high intensity LED: **Flash Max P3** (Hexagon, Denmark) (**4000 mW/cm**² for 1 or 3 seconds) and with a conventional LED: Ledmax 450 (Hilux, Benlioglu Dental Inc., Kulzer, India) (450 mW/cm² for 20 seconds)	The group of specimens that received a high amount of total light energy had high diametral tensile strength, while the group receiving low total light energy had lower diametral tensile strength.	Curing time of an ultra-high intensity LED curing unit influences the diametral tensile strength of packable composite resin.
(Vinagre *et al.*, 2019)	Compare the pulp chamber temperature rise induced by four **LED light-curing units in different curing modes**.	Extracted human premolars were submitted to random curing modes of different curing-lights: **Bluephase 20i** (Ivoclar Vivadent, Schaan, Liechtenstein) (1200 or **2000 mW/cm²**), Demi Ultra (Kerr, Orange, CA, USA) (1215 or 1330 mW/cm²), **S.P.E.C. 3** (Coltene, OH, USA) (1600 or **3000 mW/cm²** and), and **VALO** (Ultradent, UT, USA) (1000, 1400 or **3200 mW/cm²**).	There was a significant pulp temperature rise for both high and low-energy modes.	A positive correlation between radiant exposure and pulp temperature variation was determined.
(**Radiant emittance** according to the manufacturer)				

Table 7. Performance of High-power LED LCUs- *in vivo* evidence.

Article (Author/Year)	Objectives	Materials and Methods	Results	Conclusions
(Ward *et al.*, 2015)	Evaluate the clinical performance of brackets cured with a **high-intensity LED with a shorter curing time**.	Thirty-four patients and a total of 680 brackets were examined. The maxillary right and mandibular left quadrants were cured with **VALO Ortho** (Ultradent, UT, USA). The maxillary left for 6 seconds with a **high-intensity (3200 mW/cm^2)** and the mandibular right for 20 seconds with a standard intensity (1200 mW/cm^2).	No significant differences in the proportion of bracket failures were noted between the two curing methods.	Both methods showed bond failure rates low enough to be considered clinically sufficient. The use of LED curing units with high-intensity and short curing time may be considered an advantage due to the reduced chair-time.
(Runnacles *et al.*, 2015)	Investigate pulp temperature rise in human premolars during exposure to a **light curing unit using selected exposure modes**.	Eighty volunteers with intact first upper premolars requiring extraction for orthodontic reasons were sequentially exposed to the radiation of a polywave LED LCU: **Bluephase 20i** (Ivoclar Vivadent, Schaan, Liechtenstein) using different exposure modes: 10 seconds either in low or high, 5 seconds in turbo and 60 seconds in high intensities.	The highest peak and highest variation in temperature was a result of 60 seconds exposure in high-intensity (mean radiant emittance of 1244 mW/cm^2). On the other hand, 5 seconds in turbo intensity (mean radiant emittance of **2204 mW/cm^2**) and 10 seconds in high-intensity resulted in significantly lower values. 10 seconds in low intensity (mean radiant emittance of 656 mW/cm^2) produced the lowest values.	Exposing tooth to polywave LED LCU develops significant increase in pulp temperature in all exposure modes, considering that the higher the radiant exposure delivered, the more the pulp temperature increases. Overall, all values were lower than the potential damage threshold temperature increase of 5.5 ° C.
(Oz, Oz and Arici, 2016)	Compare the clinical failure rates and the in-vitro bond strengths of metal brackets bonded with **different LED devices and curing times**.	Forty patients were included in the clinical part of this study. The adhesive in group 1 was cured for 10 seconds with Elipar S10 (3M Unitek, Monrovia, Calif) (1600 mW/cm^2) and the adhesive in group 2 for 3 seconds with **VALO Ortho** (Ultradent, Utah, USA) (**3200 mW/cm^2**). *In-vitro* performance was also assessed by bonding brackets to extracted premolars using the same curing lights and curing times.	Clinical bond failure rates were 2.90% for Elipar and 3.16% for VALO. The difference in bracket failure rates between the two LED devices was not statistically significant. No statistically significant difference was found between the *in-vitro* bond strengths of the groups.	The use of high-intensity LED units for bracket bonding can save chair-time without increasing failure rates.
(**Radiant emittance** according to the manufacturer)				