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Reporting of light irradiation conditions in 300 laboratory studies of resin-composites

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ABSTRACT

Objective. To evaluate how the light delivered to resin-composites was described in recent articles.

Method. PubMed was searched for 300 articles published between January 2017 and May 2018 with keywords relating to photocuring of dental materials. The articles examined a wide range of resin-composite properties and performance. For each article, the information provided about the light curing unit (LCU), the light curing conditions and the characteristics and quantity of the light used in the study were recorded. Specifically, the type of LCU used; the irradiance; how the irradiance was measured; the exposure times; whether the light energy (radiant exposure) received by the specimen was determined, or if only the light output at the LCU tip was measured; whether the distance between the tip of the LCU and the specimen was reported; and whether the emission spectrum from the LCU was reported. Where possible, the resin manufacturer's *minimum energy requirement* (MER: the product of the recommended minimum exposure time and irradiance) was compared to the radiant exposure delivered to the specimen.

Results. Of the 300 articles examined, 217 were published in 2017 and 83 in 2018. Of these articles, 130 (43%) were found in open access journals, and 170 (57%) were in subscription-based journals. The name of the LCU used was not provided in 31 articles, 14 articles did not provide the exposure time, and 227 articles did not report the distance to the specimen.

An irradiance value was reported in 231 articles, but this was the irradiance received by the specimen in only 48 instances. The emission spectrum from the LCU was reported in 15 articles. There was a large range in the radiant exposures from below 10 J/cm^2 to greater than 100 J/cm^2.

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Significance. The majority of articles from 2017 and early 2018 did not include sufficient description of the characteristics and quantity of the light received by the resin-composite specimens to allow the study to be replicated. It is recommended that future articles should report: (1) the identity of the LCU used; (2) the radiant exposure received by the specimen (J/cm^2); and (3) appropriate reference to the emission spectrum from the LCU.

1. Introduction

The use of light-cured resins has revolutionized modern dentistry. With the agreement of many nations to phase down the use of amalgam as part of the Minamata agreement [1,2], the light curing unit (LCU) will become an indispensable piece of equipment in almost every dental office. However, despite the routine use of the LCU both in dental offices and laboratory studies, the importance of the characteristics (wavelength and the beam profile) of the light from the LCU and the quantity of the light received by the specimen (radiant exposure) are poorly understood and described [3–6]. Within a resin-composite the degree of conversion, which describes the extent to which monomer has been converted (cured) into a polymer, is related to both the spectral radiant power (W/nm) and the radiant exposure received by the resin-composite (J/cm^2) — the latter value is calculated from the product of the irradiance (W/cm^2) received and the exposure duration. In a preliminary study [7] that examined 100 articles from 2010 to 2012, it was reported that it was impossible to determine how much light energy (radiant exposure) was delivered to the resin-composites in 46 (46%) articles. It was also reported that 40 of the 54 articles where the light energy could be quantified, delivered more than twice the minimum radiant exposure recommended by the resin manufacturers to photocure the resin specimens. They considered that such radiant exposure far exceeded the MER values recommended by the manufacturers, and so did not reflect "clinical reality". Since long-term (5 + years) randomized clinical trials are often unfeasible before a product is released on the market [8,9], well-designed laboratory studies are an essential means to evaluate photocured resin materials. We can divide these laboratory studies into two main categories that we will call *Type I* and *Type II*.

Type I studies are primarily concerned with the aspects and outcomes of the photocuring process itself. These studies include measurements (some in real time) of the light transmission, depth of cure (DoC), degree of conversion (DC), cell toxicity, shrinkage kinetics, early modulus development, shrinkage stress (within a defined host environment) and cuspal deflection. In such studies, the characteristics (wavelength) and quantity (radiant exposure) of light received by the resin-composite specimen should be reported. These values should also correspond to what a dentist could be expected to deliver in "clinical reality". This may, or may not, be the same as what the manufacturer recommends because many dentists deliver a lower radiant exposure than the minimum that is recommended by the resin-composite manufacturer [7,10,11]. Dentists will often use the same exposure time for all the resin-composites that they light-cure [3]. They often hold the LCU tip at some distance away from the resin-composite [3], and the LCU often moves or is held at an angle to the surface of the restoration, thus decreasing the radiant exposure received by the resin [10–12].

In contrast, *Type II studies* are concerned with the behavior of the material, particularly mechanical strength properties. When evaluating such resin-composite properties, different non-clinical specimen shapes and sizes are used. Rectangular cross-section bars are used for 3-point flexure strength measurements. Similar bars with a small central crack are used in fracture-toughness studies, and short solid cylinders are used for compressive creep experiments. In these cases, the maximum values for the investigated properties of the resin-composite are being examined, and it is deemed appropriate to irradiate the resin-composites from multiple directions (e.g., from the top, bottom and sides) with longer irradiation times than would be the case clinically. In such cases, it is not necessary to match "clinical reality", but it is useful to know the emission spectrum of the light and the radiant exposure (characteristics and quantity of the light) that was delivered to the specimen.

It has been reported that many studies cannot be replicated or reproduced, especially among different laboratories [13–15]. One reason may be that a study can only be replicated, or the results reproduced if the conditions under which the specimens have been fabricated and stored before measurement have been reported, but this information is rarely provided. In an attempt to address such issues, the *Academy of Dental Materials* has produced a range of guidelines for investigators to follow so that, in principle, the experiments could be replicated [16]. In addition, the *International System of Units* (SI) nomenclature should be used by authors so that all readers know what is being described.

In radiometry, the radiant power (radiant flux) describes the energy emitted or received per unit time. The SI unit for radiant power is a Watt which is defined as one Joule per second. The irradiance is the radiant power that is received, not emitted, by a surface divided by the area. The SI unit for irradiance is W/m^2 [6,17], although in dentistry it is usually expressed as mW/cm^2. The irradiance value that is frequently reported is often not the irradiance received by the specimen but is instead the radiant exitance from the LCU. Although the radiant exitance may be the same as the irradiance at 0 mm distance from the light tip, this may not describe what the specimen actually receives because the specimens are often several millimeters away from the LCU tip. Furthermore, an irradiance value cannot describe how powerful a curing light is because the area of the tip is part of the calculation and a

curing light can deliver a high irradiance, but yet not be very powerful. For example, if the same radiant power is received, decreasing the light tip diameter from 10 to 7 mm will halve the tip area and double the irradiance.

2. Theoretical background

The following quantum and photochemical background describe the relationships between a photon of light and the photoinitiator. These relationships explain why two curing lights that deliver the same radiant power or irradiance but have different emission spectra may produce different outcomes when photo-curing a resin-composite.

2.1. *Electromagnetic radiation and quantized absorption processes*

Visible light is electromagnetic (EM) radiation. The spectrum of light that is visible to the human eye ranges from violet (ca. 400 nm) to red (700–750 nm). According to the Planck–Einstein relationship, a photon is a single unit (quantum) of EM radiation with energy (E) that is numerically equal to Planck's constant (h) times the frequency (ν) of light:

$$E = h\nu = \frac{hc}{\lambda}$$

where c is the speed of light in vacuum and λ is the wavelength, and the frequency equals the speed of light divided by the wavelength. Since both (h) and (c) are constants, the energy carried by each photon is inversely related to its wavelength (λ). Provided that the photons have the same wavelength or frequency, they will carry the same photon energy, even if one was emitted from a quartz tungsten halogen curing light and the other came from a light emitting diode (LED) curing light. In the past, accurately measuring the radiant power, the irradiance, and the spectral radiant power from a light source required costly equipment. However, the price of spectrophotometers and integrating spheres has fallen, and there are integrated packages of equipment available from several manufacturers [18–21] that can quickly and easily provide accurate radiometric measurements of the light from LCUs.

2.2. *Photoinitiators and photochemical reactions*

Generally, there are two types of photoinitiators used in dentistry:

Type I photoinitiators have a high quantum yield and thus require fewer photons to generate a free radical than **Type II** initiators [22–24]. These initiators do not need additional co-initiators because they break down directly into one or more free radicals when they absorb photons at the required wavelengths of light. Examples of **Type I** initiators are: Lucirin TPO and derivatives of dibenzoyl germanium (such as Ivocerin®).

Type II photoinitiators (e.g., camphorquinone [CQ] and phenyl propanedione [PPD]) require a secondary electron transfer agent (this is typically an amine *electron accepting* agent) to generate a free radical [22]. Thus, when they absorb photons at the required wavelengths of light, they produce free radicals more slowly and are less efficient than **Type I** initiators.

Camphorquinone (a **Type II** initiator) has a broad absorption spectrum with a maximum absorption of blue light close to 468 nm, and ultraviolet light below 320 nm. In contrast, Lucirin TPO (a **Type I** initiator) absorbs light only below 420 nm, with maximum absorption close to 385 nm [23,24]. Initiators such as Ivocerin® and PPD have broader absorption spectra and are activated by radiation within both the violet and lower blue wavelength color ranges. For example, although Ivocerin® is most reactive to violet light around 408 nm, it is also very sensitive to wavelengths of light between 400 and 430 nm, but not to blue/green wavelengths above 460 nm [24].

The *first law of photochemistry* [Grotthuss–Draper law] states that light must be absorbed by a chemical substance for a photochemical reaction to take place. This reaction is a quantum process, in accordance with the Planck-Einstein relationship, as mentioned above. So, electrons in certain specific chemical groups within a photoinitiator (PI) molecule *must receive photons of energy* ($h\nu$) – and thus of frequency/wavelength – *corresponding* to the energy difference (ΔE_{PI}) between their excited state (PI*) and their ground state. Thus, the frequency/wavelength of these photons matters and if the photon energy does not match ΔE_{PI} then, *irrespective of the irradiance*, *the* PI *remains un-excited* and cannot react further to produce free-radicals [15]. A partial everyday analogy may be made with postal deliveries: If a package is too large to fit through a letterbox, the package cannot be delivered, no matter how many attempts are made.

The *second law of photochemistry* [Stark–Einstein law] states that for each photon of light absorbed by a chemical system, only one molecule can be activated for a photochemical reaction to occur. This is also known as *the law of photochemical equivalence*. Since the lifetime of an excited species is short ($\sim 10^{-8}$ s), an excited photoinitiator molecule (PI*) that has just absorbed one photon has a low probability of absorbing another photon before it becomes deactivated. The excited photoinitiator molecules typically react with other species, including monomer molecules, to produce free radicals. The ratio of the number of molecules undergoing reaction in a given time, to the number of photons absorbed, is known as the photon yield, or *quantum yield* (Φ). The typical quantum yield will be less than 1. Moreover, some radicals may initiate chain reactions, thus leading to higher reaction rates than otherwise expected and quantum yields greater than 1 are possible for some photo-induced chain reactions.

2.3. *Objectives*

When studying photocuring of resin-composites, researchers are investigating the interaction between light, the fillers, the monomers, and the initiator molecules within the resin-composites. Consequently, the characteristics and quantity of the light received by the resin should be reported. Namely: (i) the emission spectrum from the LCU, (ii) the exposure time, (iii) the irradiance (W/cm^2), and (iv) the radiant exposure (J/cm^2) that is received by the resin composite specimen [5,6,25,26]. This study examined the extent to which these crit-

ical features were specified in 300 articles that were published from 2017 until May 2018. Three hypotheses were tested:

1. Recent articles provide the necessary critical information about the output from the light-curing unit (LCU) used in the study (light characteristics).
2. Recent articles report, or it is possible to calculate, the radiant exposure (energy) delivered to the resin-composite surfaces used in the study (light quantity).
3. The resin-based composite (RBC) specimens in the articles received the minimum radiant exposure (MER) recommended by the resin-composite manufacturers.

3. Materials and methods

A manual search of dental articles in PubMed from January 2017 until May 2018 was conducted by the authors using different combinations of the terms: 'dentistry', 'resin', 'depth of cure', 'bond strength', 'light curing', or 'curing light' until 300 articles were found in which dental curing lights were used to photocure dental resins. The full version of every article was read by two of the authors and a consensus achieved regarding the information given about the curing light and how the characteristics and quantity of the light received by the specimens in the study were described. It was noted whether the article was published in an open access or a subscription-based journal. Specifically, we looked for: the curing light (LCU); how and where the irradiance was measured; the exposure times; the distance between the tip of the LCU and the specimen; the emission spectrum; and the energy (radiant exposure) received by the specimen. The radiant exitance (tip irradiance) values were reported in five different ranges: (i) below 500 mW/cm^2, (ii) between 500 and 1000 mW/cm^2, (iii) between 1001 and 1500 mW/cm^2, (iv) between 1501 and 2000 mW/cm^2 and (v) exceeding 2000 mW/cm^2. We attempted to compare the resin-composite manufacturer's *minimum energy recommendation* (MER) to the radiant exposure delivered to the specimen. Since manufacturers rarely provide a MER, this value was calculated from the product of the recommended minimum irradiance and exposure time. The MER ranged between 10 to 25 J/cm^2. More details regarding each article are given in the Supplementary Material that is available online.

4. Results

Of the 300 articles, 217 were published in 2017 and 83 in 2018. The articles examined a wide range of resin-composite properties and performance. 130 articles (43%) were found in open access journals and 170 (57%) from subscription-based journals. 233 articles were classified as *Type I studies*, and 59 were *Type II studies*, and 8 articles were classified as a combination of *Type I* and *Type II studies*.

4.1. *Type of LCU: Table 1*

A broad range of LCUs was used in the 300 articles examined. The LCUs were categorized into three types according to how the light was produced: Quartz-Tungsten Halogen (QTH) lights, LED, and plasma arc (PAC) light sources (Table 1). Some studies used more than one type of light; thus, the total number was more than 300. There was no mention of the name of the curing light used in 31 articles, but two articles in this group did provide the type of LCU that was used.

Table 1 – Number of articles (N) and the (%) that used each type of LCU found in open access and subscription-based articles (total = 305 because some articles used more than one type of LCU).

Type of LCU used	Open access N (%)	Subscription based N (%)
LED	83 (27.2)	127 (41.6)
QTH	30 (9.8)	34 (11.1)
PAC	0 (0)	2 (0.7)
Unknown	18 (5.9)	11 (3.6)

4.2. *Method of light measurement and what was reported; Tables 2 and 3*

The articles were assigned to seven different categories according to how the light from the LCU was measured and reported, as follows: (1) by dental radiometer; (2) by spectrometer; (3) by power meter; (4) by MARC^{TM} (BlueLight Analytics Inc, Halifax, NS, Canada) systems; (5) irradiance reported but determined via an unspecified method; (6) irradiance not reported; (7) a combination of methods were used. Table 2 shows that 132 articles reviewed did not specify how the reported irradiance value was measured and 69 did not report an irradiance value. Of these 69 articles, 2 articles measured the light output with a dental radiometer, 2 articles measured the light with the MARC^{TM} system, and 1 used a spectrometer, but they did not report any irradiance value. Thus no irradiance value was reported in 69 articles (Table 3) and the irradiance was not measured in 64 articles (Table 2). Although a UV/VIS spectrometer and some MARC^{TM} devices can report the emission spectrum, this information was provided only in 15 of the 39 articles that used these methods (Tables 2 and 3). The distance between the light tip and the specimen was reported in only 73 articles, and the beam profile was reported in 3 articles. Out of the 231 articles that reported an irradiance value, 48 articles reported that they measured the irradiance received by the specimen (Table 3).

Table 2 – Method used to measure the characteristics of the LCU, or the light received by the specimen.

Light measurement used	Number of articles, N and (%)
Dental radiometer	50 (16.7)
Spectrometer	10 (3.3)
Power meter	11 (3.7)
MARC^{TM}	29 (9.7)
Not specified, but a value was reported	132 (44.0)
Not measured	64 (21.3)
Two or more methods were combined	4 (1.3)
Total	300

Table 3 – Number of articles that reported the following light characteristics: an irradiance value, irradiance received, emission spectrum, distance between the light tip and the specimen, reader able to calculate the radiant exposure, and the beam profile.

	Irradiance value reported	Was the light received by the specimen measured?	Emission spectrum	Distance between light tip and specimen	Radiant exposure (calculated)	Beam profile
Yes	231	48	15	73	225	3
No	69	252	285	227	75	297

Table 4 – Type of LCU used and the irradiance values reported by the authors (Number and %). Note: The total number of incidences that a type light was used is 338 because some articles used several different types of LCU that delivered different irradiance values in the same study.

Irradiance [mW/cm^2]	LED Number and (%)	QTH number and (%)	PAC number and (%)	Unknown LCU number and (%)
<500	6 (2.5)	8 (11.9)	1 (50.0)	1 (3.3)
500–1000	70 (29.3)	44 (65.7)	0 (0)	2 (6.7)
1001–1500	95 (39.7)	0 (0)	0 (0)	2 (6.7)
1501–2000	19 (7.9)	1 (1.5)	0 (0)	0 (0)
>2000	10 (4.2)	0 (0)	0 (0)	1(3.3)
Ramp cure	8 (3.3)	0 (0)	0 (0)	0 (0)
Unknown	31 (13.0)	14 (20.9)	1 (50.0)	24 (80)
Total Use	239	67	2	30

4.3. *Radiant exitance (Tip irradiance) values: Table 4*

Overall, irradiance values between 500 and 1000 mW/cm^2 were reported in 116 instances and between 1001 and 1500 mW/cm^2 in 97 instances. The majority (239) of the articles used LED curing lights (Table 4). Since some researchers used more than one LCU or reported more than one irradiance value, the total number of irradiance values reported exceeds 300.

4.4. *Irradiance reported vs. type of study: Table 5*

The type of study reporting various ranges of irradiance values was noted (Table 5). As explained in the Introduction, the *Type I* classification included studies on light transmission, the degree of conversion, depth of cure, hardness, shrinkage, bond strength, and cell studies/toxicology. In several articles, more than one property was studied. Of the 300 articles examined, more than half (163) measured the bond strength between the resin composite and various substrates. Mechanical properties were classified as *Type II* studies and accounted for 47 articles (Table 5). Of note, 4 *Type II* studies did not report an irradiance value.

4.5. *Radiant exposure (J/cm^2) received by the specimen and manufacturer's Minimum Energy Recommendation (MER): Fig. 1, Tables 3 and 6*

In most articles, the radiant exposure was not *explicitly* reported. Instead, it was necessary to calculate the value by multiplying the reported irradiance by the exposure time that was used (Fig. 1). The radiant exposure could be ascertained in 225 articles (Table 3) but in most articles, this was not based on the irradiance received by the specimen but was instead the radiant exposure at the light tip. In 128 studies the radiant exposure did not exceed the MER, and as shown in Fig. 1, in 11 instances (3 in *Type I* and 8 in *Type II studies*) more than 100 J/cm^2 was delivered. In 98 articles, the MER could not be ascertained due to a lack of information about the light or the RBC.

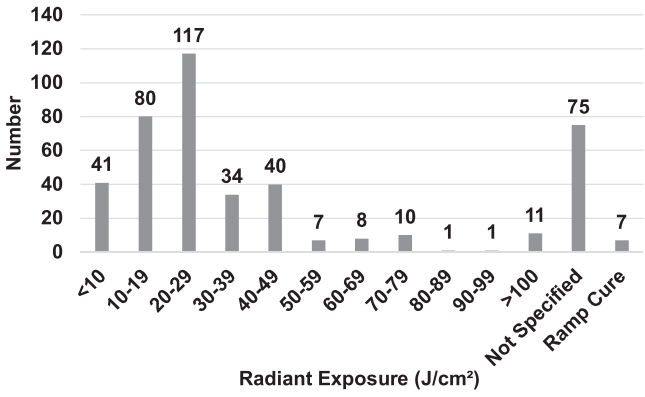

Fig. 1 – Number of instances where each radiant exposure range [J/cm^2] was delivered. Radiant exposures were calculated from the product of the exposure time and the irradiance. Note: some articles used more than one LCU or delivered more than one irradiance value.

5. Discussion

Out of the 300 articles reviewed, 29 (9.5%) made no mention of the type of curing light that was used in the study, 69 (23%) of the articles did not report any irradiance value, 227 (76%) articles did not report the distance between the light tip and the specimen, and 285 (95%) articles did not report the emission spectrum from the LCU. Thus, the first hypothesis that contemporary articles provide the necessary critical information about the output from the light-curing unit used in the study was rejected. Of note, although 18 of the 29 articles that did not report which LCU was used in the study were found in

Table 5 – Type of study and number of articles reporting specified ranges of irradiance [mW/cm^2] values in *Type I* and *Type II studies* (N and % of articles within each category).

Irradiance [mW/cm^2]	Type I Study					Type II Study		
	Light transmission N [%]	Degree of conversion N [%]	Depth of cure N [%]	Hardness testing N [%]	Shrinkage N [%]	Bond strength N [%]	Cell studies N [%]	Mechanical properties N [%]
<500	3 (9.7)	4 (5.3)	0 (0)	3 (5.0)	2 (7.7)	4 (2.5)	1 (3.0)	5 (10.6)
500–1000	7 (22.6)	26 (34.7)	6 (85.7)	15 (25.0)	9 (34.6)	55 (33.7)	10 (30.3)	17 (36.2)
1001< × >1500	13 (41.9)	25 (33.3)	1 (14.3)	24 (40.0)	8 (30.8)	43 (26.4)	13 (39.4)	17 (36.2)
1501≤ × >2000	2 (6.5)	5 (6.7)	0 (0)	6 (10.0)	4 (15.4)	7 (4.3)	0 (0)	2 (4.3)
>2000	2 (6.5)	4 (5.3)	0 (0)	4 (6.7)	0 (0)	3 (1.8)	2 (6.1)	1 (2.1)
Ramp cure	2 (6.5)	3 (4.0)	0 (0)	3 (5.0)	2 (7.7)	2 (1.2)	0 (0)	1 (2.1)
Unknown	2 (6.5)	8 (10.7)	0 (0)	5 (8.3)	1 (3.8)	49 (30.1)	7 (21.2)	4 (8.5)
Total	31	75	7	60	26	163	33	47

open access articles, the remaining 11 articles were found in subscription-based journal.

An irradiance value was reported in 231 (77%) articles, but only in 48 (16%) studies could it be determined that this value was the irradiance that the resin-composite received. In the remaining 183 articles reporting an irradiance value, it was measured at the light tip (0 mm distance). This value is different from what the specimen might have received [12,27,28] making it impossible to calculate the radiant exposure delivered to the specimen. Thus, the second hypothesis was rejected because it was not possible to ascertain the radiant exposure (energy) delivered to all the RBC specimens (Table 3).

Tip irradiance values between 500 and 1000 mW/cm^2 were reported in 116 instances and between 1001 and 1500 mW/cm^2 in 97 instances. Many of the *Type II studies* that examined the behavior of the RBC, particularly mechanical strength properties, used low irradiance values and 4 articles did not report the irradiance (Table 5). Out of 47 *Type II studies*, 22 reported an irradiance that was below 1000 mW/cm^2 and only 3 reported an irradiance that was greater than 1500 mW/cm^2. LED curing lights now dominate the market [3] and more than half of the articles that used LED curing lights (124 of the 239 articles) provided an irradiance value that was greater than 1000 mW/cm^2. However, the nature of LEDs means that, unlike QTH lights, they can only produce a narrow emission spectrum and the emission spectra among different brands of LED curing lights can be markedly different [6]. Furthermore, to produce a broader spectrum of light, some LED curing units now contain multiple LEDs. Thus, the emission spectrum from the LED lights, in particular, should be reported, but only 15 articles reported this information. Also, depending on the optical design of the LCU, both spectral and radiant emittance may be non-uniformly distributed across the end of the light tip [29], and some regions of the light tip can emit very different wavelengths of light than other regions. This was reported in the three articles [30–32] that provided irradiance beam profiles from the LCUs used in these studies (Table 3).

It was impossible to either accept or refute the third hypothesis that the RBC specimens in the articles received the minimum radiant exposure recommended by the resin-composite manufacturers. This was because 69 articles reported no irradiance value and for the majority of the remaining that did report a value, it was measured at the light tip. Since the irradiance and the beam profile [6] measured directly at the light tip can be different from those measured at some distance [27,28], we were unable to determine the radiant exposure received by the specimen unless the specimen was located at the light tip (0 mm) or the irradiance received was reported. However, we did attempt to classify articles (Table 6) into the "more energy emitted at the tip or at the RBC than recommended by the manufacturer" group if the values used for curing the specimen were greater than the MER values provided by the manufacturer's recommendation. There was a large range in the radiant exposures, from below 10 J/cm^2 to greater than 100 J/cm^2. For 128 (43%) of the articles, the radiant exposures did not exceed the MER and thus the specimens were unlikely to receive more than the MER. For 47 articles, (16%), the energy delivered at the tip or at the RBC exceeded the minimum recommended by the manu-

Table 6 – Number of articles (and %) where the radiant exposure at the tip or at the RBC exceeded the minimum amount recommended by the manufacturer (MER).

Does the amount of light exceed the MER values?	Number of articles	% of the total number articles
Yes	47	15.7
No	128	42.7
Depends on material and parameters	27	9.0
Not enough information available about the light or the RBC	98	32.7
Total	300	100

facturers (Table 6). In 27 (9%) of the articles, several different variables were used within the study and whether the radiant exposure exceeded the manufacturer's minimum recommendations varied according to different aspects or products used in the study. There were 3 *Type I* articles and 8 *Type II* articles that had radiant exposures greater than 100 J/cm^2. This was at least more than 4 times the MER, which ranged from 10 to 24 J/cm^2 depending on the brand of RBC used.

Several previous articles [5,6,25,26] have described *why* the light output from a curing light should be fully described. After reviewing these 300 articles, it is clear that an adequate description of the light received by resin-composite specimens in dental research continues to remain mostly omitted in the majority of contemporary research articles. This lack of detail may explain why the results of many studies cannot be replicated [13–15] as the reader is left guessing the characteristics and quantity of the light the specimen actually received. To overcome this obstacle, it is recommended that future articles should report the identity of the LCU used and the radiant exposure received by the specimen (J/cm^2) and make appropriate reference to the emission spectrum from the LCU.

5.1. *Study limitations*

The authors do not claim to have included every article published between January 2017 and May 2018 that used a curing light. After searching PubMed, we found 130 (43%) articles in open access journals and 170 (57%) in subscription-based journals. Although we were surprised by the high number of open-access publications that were freely available online, we considered the total number of 300 articles to represent a good cross-section of the current state of reporting the light delivered in dental research. We have noted that the irradiance and radiant exposures reported in the present study might themselves be inaccurate because most of the articles reported the irradiance at the light tip and many studies did not state the distance between the light tip and the specimen. Also, the accuracy of the radiometers used to measure the LCUs in these studies is unknown [33–35]. Consequently, the irradiance values and radiant exposures reported in these articles may also be inaccurate.

6. Conclusions

Within the limitation of the study that examined 300 articles published in 2017 and early 2018 that used dental LCUs, the following conclusions were made:

1. Of the 300 articles examined, 29 articles made no mention of the type of curing light used in the study, 69 did not report an irradiance value, 227 did not report the distance between the light tip and the specimen, and 285 did not report the emission spectrum from the LCU.
2. The characteristics (wavelength in nm) and quantity (radiant exposure, J/cm^2) of light received by the resin-composites used in the articles were in most cases not adequately described. This lack of information will hamper the replication of studies that use a curing light.
3. Where we were able to approximate the radiant exposure received by the RBC, there was a large range from below 10 J/cm^2 to greater than 100 J/cm^2.

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