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Robust spectrometer-based methods for characterizing radiant exitance of dental LED light curing units

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ABSTRACT

Objectives. Firstly, to assess light output, from a representative range of dental light curing units (LCUs), using a new portable spectrometer based instrument (checkMARC™) compared with a "gold standard" method. Secondly, to assess possible inconsistency between light output measurements using three different laboratory-grade thermopile instruments.

Methods. The output of four blue-dental LCUs and four polywave blue-and-violet-LCUs was measured with two spectrometer-based systems: a portable spectrometer instrument and a benchtop Integrating Sphere fiber-coupled spectrometer system. Power output was also recorded with three thermopiles according to ISO 10650-2. Beam profile images were recorded of LCU output to assess for spatial and spectral beam uniformity.

Results. Power recorded with the portable spectrometer instrument closely matched the 'gold standard' Integrating Sphere apparatus calibrated according to International Standards. Radiant exitance for the eight LCUs differed significantly between the three thermopiles. Light source to thermopile sensor distance influenced recorded power significantly ($p < 0.05$), indicating the severe limitations of thermopiles for absolute measurements. Polywave LCU beam profiles demonstrated output spectral heterogeneity.

Significance. Spectrometer-based methods are capable of overcoming the limitations inherent with thermopile-based measurement techniques. Spectrometer based measurements can fulfill the intention of ISO 10650.

1. Introduction

1.1. The challenge of photo-polymerization in dentistry

Effective photo-polymerization is a prerequisite for the long term clinical success and quality of light-activated resin-based composite (RBC) restorations. Amongst the factors which influence the polymerization efficiency of (multi-)methacrylate RBCs, the light curing unit (LCU) is a key extrinsic variable [1,2]. Whilst quartz tungsten halogen (QTH) LCUs have been the mainstay of dental practice for decades [3] blue light emitting diode (LED) units have replaced them

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as the most popular type because they are compact, portable, energy efficient and have potentially superior service life [4,5].

1.2. The challenges of measuring radiant output of dental LED-LCUs

Unlike point light sources or collimated laser sources, dental LED-LCUs pose unique challenges. Hand-held dental radiometers commonly used for measuring irradiance are inaccurate and may vary within the same model [6]. Results from such 'dental radiometers' are influenced by differences in measurement time, spectral sensitivity and mismatch between the instrument sensor aperture and the LCU area [7–9].

Attention to detail is required for accurate performance of all radiometric measurements. Meaningful reporting of radiometric data requires appropriate nomenclature and precise physical definitions of key terms such as radiant exitance [10]. The diversity of: (i) LCU types (gun or pen style, corded or cordless, fixed or removable lens cap or fiber optic light guide) and (ii) irradiation protocols available (pulse, soft start and modulated cure) complicate the measurement of their power output, spectral and irradiance characteristics. The following major challenges exist:

- The diameter of the LCU optic or exit window may range from <5 mm to >10 mm and there may be non-uniformity of the light beam-profile.
- The target surface area (diameter) will vary with different clinical scenarios or laboratory test setup requirements.
- The LCU optic – "target" distance can vary in clinical practice from zero to 10 mm and the irradiance declines over this distance.
- LED-LCUs may incorporate one or more LED-chips each outputting a different wavelength range.
- The irradiation time can vary from 1 s to 20 s or more. Power output varies over time with pulsed or modulated cure protocols.

The available instrumentation for measuring output includes (i) light collection devices (cosine correctors, integrating spheres), (ii) bandpass filters to isolate specific spectral regions, (iii) thermopiles, (iv) spectrometers. The selection of appropriate combinations is challenging for the reasons outlined above. Integrating sphere light collection devices coupled to spectro-radiometers are considered as the gold standard for the optical characterization of dental LCUs in the laboratory. Total radiant power and spectral power as a function of wavelength may be determined. Recently introduced modified integrating sphere instruments (checkMARC™ from Bluelight analytics and the larger BTS256-Hi from Gigahertz-Optik GmbH, Türkenfeld, Germany) make it practical to conduct such measurements in dental practice.

1.3. Consideration of the existing ISO Standard for LED-LCUs

ISO 4049 [11] is concerned with polymer based restorative materials and ISO 10650-2 [12] exists to standardize the requirements and test methods for light curing units (LCUs). ISO 10650-2 outlines a standardized protocol for measuring the output of dental LED-LCUs. It addresses some of the issues mentioned above but fails to deal with others. Because of the relatively slow response-time inherent with thermopile detectors, LCUs with short irradiation times cannot be measured reliably. When ISO 10650-1 was published in 2004 it identified 400–515 nm as the blue region for LCUs. The standard was published before multi-peak or polywave LED-LCUs were marketed, designed to cure materials containing alternative photo-initiators. The cut-off point between violet and blue light may be identified as 425 nm spectrally. The development of high irradiance (>1500 mW/cm^2) LED-LCUs with very short irradiation times coupled with the introduction of spatially non-uniform multi-wavelength sources have increased the need to revise these standards for contemporary dental practice.

ISO 10650-2 (2007) specifies measurement of radiant exitance for three discrete wavelength regions using a series of four long-pass filters (Table 1). The ISO 10650-1 source document requires that the entrance aperture of the radiometer be greater than the cross-sectional area of the optic tip (light-guide exit window) and that the edge of the optic tip should be at least 2 mm from the edge of the radiometer entrance aperture so that all radiant emission is measured by the radiometer. The protocol involves sequentially measuring radiant exitance with specified filters and calculating and reporting light transmission in the ranges (a) 190–385 nm, (b) 400–515 nm and (c) above 515 nm. Region (a) includes not only the ultraviolet region but also the near-blue wavelength region of around 380 nm. Unfortunately the 385–400 nm region is unaccounted for, although several dental LED-LCU sources emit considerable radiant energy in this region, since the 385–415 nm bandwidth is important for some alternative photo-initiators. In Section 5.2.2, it specifies that the radiant exitance between 190 and 385 nm should be less than 200 mW/cm^2. The region above 515 nm reaches approximately to 1100 nm, which is the detection limit of the measurement device specified in the Standard. According to Section 5.2.3, the upper limit for radiant exitance above 515 nm should be not greater than 100 mW/cm^2. No requirement is given for radiant exitance (or power) in the 400–515 nm wavelength region

Table 1 – Long-pass filters according to ISO 10650-2 and wavelength regions of interest. NB In our work, measurements were also conducted for wavelengths between 190 and 515 nm, using filters *a* and *d*.

Filter type	Quartz (SQ1)	Schott GG385	Schott GG400	Schott OG515
Transmission	*a* > 190 nm	*b* > 385 nm	*c* > 400 nm	*d* > 515 nm
[0,1-2]ISO 10650-2 procedures and corresponding wavelength regions (nm)	*a–b* 190–385	*c–d* 400–515	*d* >515	