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Curing-light attenuation in filled-resin restorative materials

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ABSTRACT

Objective. To characterize the attenuation of the curing light in filled resin restorative materials (FRRMs) to aid understanding of curing depth.

Materials and methods. One hundred and eighty materials of various shades from several manufacturers were tested in various ways. One set (66 materials) was used to determine the applicability of Lambert's Law using a quartz-tungsten-halogen curing light (Optilux 400, Demetron Research) by measuring the transmitted light with a dental radiometer (Cure Rite, EFOS) for successive thicknesses of ground 10 mm diameter specimens from 3 to 0.5 mm in 0.5 mm steps. A second set (17 materials) were similarly tested with separate specimens from 1 to 5 mm in thickness using a transmission densitometer (DT1405, RY Parry) fitted with a curing-light dichroic filter. For a third (overlapping) set (165 materials), the 1 mm pure (reflectance-free) optical density (D_1 value) was determined from two specimens, ∼1 and ∼2 mm thick using the densitometer as above. From D_1 the critical thickness (x_{CRIT}), identified as depth of cure (DoC) for an excess surface exposure factor of 2, was calculated.

Results. Lambert's Law was found to hold with no evidence of appreciable differential absorption effects. Attenuation coefficient and D_1 were significantly correlated ($P < 1 \times 10^{-13}$). D_1 varied between about 0.23 and 0.72, for corresponding x_{CRIT} values of 1.3 and 0.4 mm. There was no correlation between D_1 and reflectance ($P > 0.09$), and no systematic effect due to shade letter, but a highly significant ($P < 7.5 \times 10^{-8}$), but weak (−0.066 mm/unit), correlation between shade number and D_1.

Significance. Depth of cure can be calculated directly from the D_1 value determined via simple optical density measurements on two specimens providing that (a) an irradiation time can be determined for the surface of a specimen to be "sufficiently" cured (i.e. for DoC = 0 precisely), and (b) an excess internal surface exposure ratio can be chosen such that the corresponding DoC is attained in a practicable irradiation time.

1. Introduction

One of the problems associated with the use of direct-placement, visible light-cured, filled-resin dental restorative materials is the decrease in curing-light intensity with depth in the material. The intensity of light (strictly, the irradiance), at a given depth and for a given irradiation period, is a critical factor in determining the extent of reaction of monomer into

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polymer, typically referred to as "degree of conversion" [1–3], which is significantly associated with the values of mechanical properties [4], biocompatibility [5], colour stability [6], and as such would be expected to be associated with the clinical success of the restoration. It is therefore important to achieve sufficient irradiance at the bottom surface of each of the incremental layers used in building up the restoration. The concept of the point of sufficiency in this respect is called "depth of cure" (DoC).

Absorption and scatter within the material are the major factors associated with light attenuation [7], other than reflection from the restoration surface [8], for this is dependent on the formulation of the material, particularly the filler size, type and content [9,10], and the shade of the material [11–13]. There are marked variations in formulation between products so that similar variation in the rate of light attenuation may reasonably be expected. Previous studies have clearly shown significant variations in depth of cure between products [14–16], which has primarily been attributed to scattering of the activating radiation, thus indirectly demonstrating differences in light attenuation between materials. However, despite these clear differences, a 2 mm incremental thickness at a minimum irradiance of 280 mW/cm^2 has been recommended [17], apparently for all filled-resin composites. Increments of up to 5 mm have also been recommended for some materials, e.g. for the product "SureFil" [18].

It thus emerges that the identification of the correct exposure, E (irradiance × time ($I \times t$)) that will achieve "complete" reaction is of continuing concern. Essentially, in order to attain the intended set of mechanical properties (which ordinarily might be understood as meaning highest strength and stiffness), and thus (presumably) to maximize the service life of the restoration, the degree of conversion of reactable vinyl groups must also be maximized. This reaction involves, typically, a diketone-amine photosensitized free-radical polymerization system, irradiated by light of wavelengths in the region of 400–500 nm. A kinetically complicated, diffusion-limited series of processes then occur in what is even initially a highly viscous medium, but one which is increasingly so. The glassy state, in which reaction rates may fall by several orders of magnitude, is approached as reaction proceeds because of the typically high degree of cross-linking arising from the bifunctional reactants. The system is also non-isothermal as a result of thermalized absorbed radiation as well as generated heat of reaction, both of which are non-uniform. The nature of free-radical polymerization is such that reaction does not come to a stop on cessation of irradiation but continues for some time afterwards, so care in defining the point at which property values are determined is required.

Those are chemical and physical issues, but there is also (self-generated) economic pressure on the dentist to minimize the time spent performing the irradiation, and thus there is an associated drive to increase the irradiance to achieve this, frequently on the erroneous [19] assumptions that total energy is the criterion [20,21], that reciprocity holds [3,22], and that the mechanical outcome is the same no matter how the exposure was obtained (i.e. I and t combinations). However, an important reaction involves the mutual annihilation of free radicals, the rate of which, therefore, depends on the square of their concentration. Thus, to assume implicitly that the rate of mutual annihilation of radicals (as opposed to being involved in chain growth) could be independent of their concentration is simply wrong, thus the network characteristics must be functions of I and t, not just E ($I \times t$). Even so, it is not within the power of the dentist to determine whether a correct exposure has actually been used.

In filled resins, the transmission of radiation is affected by a number of factors. Primarily, absorption by solutes of a purely chemistry-dependent kind, affected by species concentration, controls the transmission spectrum and is therefore dependent on the incident radiation spectrum. There is also absorption by opaque substances (pigments). These differential absorption effects also mean that the transmitted spectrum changes continuously with depth and that deviations in behaviour will occur for both concentrated absorbents and long paths. Secondly, partial reflection at all interfaces where there is a change of refractive index means that for a particulate dispersion there will be a great deal of scattering [8] and thus increased path lengths, and therefore both escape from the specimen other than at the measurement site and greater true absorption. In addition, refractive index changes with polymerization (increase) and temperature (decrease), and both change continuously through the irradiation process [23]. The molar extinction coefficients of components in pure (unfilled) resin cannot be applied to calculations without this effect being accommodated; mean path length is likely to be hard to obtain, even if worthwhile. This applies not only to the filler but also to bubbles inevitably present at manufacture as well as those introduced during handling. Other scattering mechanisms exist for very small particles [9]. Thus, it is more appropriate to refer to curing-light attenuation rather than absorption since it is not possible to disentangle the two and it is the combined effects that are relevant to the context. That is, the attenuation must be determined for the actual material and a specific irradiating spectrum. Thus, separate determinations should be made for each type of curing lamp that might be used.

The determination of the mechanical outcome of the effects of exposure necessarily involve specimens of finite thickness. Hence, since absorption and scattering of light occur, irradiance varies with distance from the irradiated surface, even if it is assumed that the common practice of overlapping spots [24–26] can be avoided [27,28] and that the still less-understood variation in irradiance from place to place within the illuminated area can be ignored. Macroscopic mechanical tests, therefore, involve either a measurement of the net effect of variation over the depth of the specimen if exposure is specified, or the hope that the mechanical properties attained are uniform over that depth for what must be guessed as sufficient to attain completion at the greatest depth, given that reciprocity may not hold.

Ultimately, the manufacturer's and the standards compliance testing laboratory's concern is to characterize a product. On the other hand, the dentist's concerns are simply to receive unambiguous instructions that will lead to a predictably satisfactory outcome, and to understand the consequences of failure to comply with these—given that material thickness is not readily controllable, irradiance is affected by problems of access (proximity of light source to material surface), and the above-mentioned economic pressure is present.