

**ASSESSMENT OF EXPOSURE AND RISKS FROM
COMPONENTS AND DEGRADATION PRODUCTS OF
COMPOSITE RESIN DENTAL MATERIALS**

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1.0 INTRODUCTION

A recent report from Health Canada (Richardson 1995), regarding mercury exposure and risks from dental amalgam, has raised questions regarding the potential risks posed by all dental restorative materials. Dental materials used to repair carious teeth are exempted from the pre-market review provisions for medical devices, published under the Canadian Food and Drugs Act (HC 1996). As a result, there are no Canadian regulatory requirements for the safety evaluation of dental restorative materials. In Canada, these materials are reviewed by a dental materials committee of the Canadian Dental Association. As well, certification is provided by the Standards Council of Canada, in the form of CSA[®] approval. However, these review procedures do not include a formal evaluation of potential health risks posed by exposures to the components and degradation products of dental materials.

Dental amalgam is 50% mercury by weight and causes continuous low level exposure to mercury vapour (see Richardson 1995). This exposure, and the potential sub-clinical impacts of mercury on the central nervous system (most notably on cognitive function (reviewed by Richardson 1995)), have led Health Canada to review its policy with respect to the use of amalgam as a safe and effective dental restorative material in Canada. Concern has been expressed that criticism of the use of dental amalgam, or any regulatory limits placed on the use of this material, will cause dental patients to seek the wholesale replacement of their amalgam fillings with alternate materials, the most common and least expensive of which is composite resin (USDHHS 1993).

The general class of dental restorative materials known as composite resins are composed of an inorganic filler, typically silica (SiO₂) or other inert glass (including zirconium oxide, ytterbium fluoride, borosilicate glass), dispersed in an organic matrix (reviewed by Smith et al. 1993). The organic matrix is composed primarily of bisphenol A glycidylmethacrylate (BIS-GMA), a polymer of methyl methacrylate. Particles of inorganic filler, generally ranging in size from 0.04 µm to 0.1 µm diameter, are added to increase hardness and wear resistance, and to improve polishability and aesthetic qualities. Various other substances are also added to these composite materials as diluents and catalysts, to increase radiopacity, to release fluoride and to increase bonding between the organic matrix and inorganic filler particles. The development and description of these materials are more extensively reviewed by Smith et al. (1993), Christensen (1989), Roulet (1987), McLean (1984), and others.

Unpolymerized methyl methacrylate may leach from set composite resins. The polymerization process is not 100% efficient (Ferracane and Greener 1984; Ruyter and Svendsen 1977), and methyl methacrylate is water leachable from set resin (Thompson et al. 1982; Tanaka et al. 1991).

Composite resins degrade enzymatically in the oral environment (Munksgaard and Freund 1990). Enzymatic

degradation releases methacrylic acid (Munksgaard and Freund 1990) and formaldehyde (Oysaed et al. 1988), into the mouths of persons bearing such fillings.

Composite resin dental restorative materials are also subject to wear due to masticatory forces, abrasive food particles and friction with opposing teeth, resulting in the steady loss of material from filled tooth surfaces (Sulong and Aziz 1990). The wear of composite resins is greater in opposing occlusal surfaces (i.e., contacts an opposing tooth during occlusion) than non-opposing occlusal surfaces (Willems et al. 1993), is greater in molars than premolars (El-Mowafy 1993), and increases as the size of fillings increase (El-Mowafy 1993).

Formaldehyde, methyl methacrylate and methacrylic acid are highly soluble (CRC 1994). The polymer and inorganic components of these filling materials are non-volatile (CRC 1994). Therefore, the primary route of exposure to components of composite resin is via ingestion with saliva, food and beverages.

As yet, no determination has been made as to what levels of human exposure may arise from these substances, or what potential systemic risks those exposures might pose. This has led some dental practitioners and others to criticize the potential indirect promotion of a dental material which does not have available the same exposure and risk information as is currently available for dental amalgam.

The purpose of this study was to rectify, in part, this lack of information. Based on published and unpublished information, exposures to major components and degradation products of dental composite resin materials were estimated for the Canadian adult population. To determine if unacceptable risks might be posed by these exposures, the estimated doses were compared to available toxicological reference doses for human ingestion exposure to these individual substances.

This study focused on BIS-GMA, its monomer methyl methacrylate, the degradation products methacrylic acid and formaldehyde, as well as silica as the inorganic filler. Other minor components of composite resins, such as catalysts, bonding agents and diluents were not evaluated due to their extremely low concentrations within composite materials generally, and to the great variation in the concentration of these components in specific commercial preparations. Only silica was evaluated as an inorganic filler as this is the predominant material used for this purpose in most commercially-available composite resins.

This evaluation is generic in nature and does not apply to any or every specific commercial resin product. A broad spectrum of published information on numerous commercial products were necessarily employed to undertake this analysis. Sufficient product-specific information on chemical composition, degradation and wear rates, could not be located on each and every composite resin product to permit a product-by-product evaluation. Therefore, it would be

unreasonable to focus this assessment on any specific product. However, the results are considered representative of this general class of dental restorative materials.

2.0 METHODS

For the present assessment, probabilistic methods (Burmaster and von Stackelberg 1991; Thompson et al. 1992) were used to estimate exposure of the Canadian population to components and degradation products of composite resin materials. It was recognized that individuals differ in the number of fillings they possess. Other variables required to estimate exposure (such as wear and degradation rates, etc.) are not precisely known, vary from individual to individual, and/or vary from dental product to dental product. These variations and uncertainties in input variables introduce variance and uncertainty into the estimates of exposure. Standard deterministic methods, which employ single point estimates of input variables, fail to recognize or quantify the variance or uncertainty in exposure estimates across a population. Also, use of worst case point estimates rather than average or typical values for input variables can result in over-estimation of exposure. Finally, probabilistic methods, employing the known, reported or best estimate of the range of values of input variables (represented as probability density functions) can provide an estimate of exposure for which some statistical likelihood can be assigned.

Exposures to the products of abrasive wear were calculated as the sum of exposures arising from occlusal and non-occlusal surfaces. These exposures were estimated with the following equations:

$$\text{DOSE}_{\text{inorg-oc}} \text{ (g/kg-day)} = \sum_{i=1}^n (W_{\text{oci}} * \text{AREA}_{\text{oci}} * \text{VOL}\%_{\text{inorgi}} * \text{DENSITY}_{\text{inorgi}}) / \text{BW} \quad (1)$$

where, $\text{DOSE}_{\text{inorg-oc}}$ is the estimated exposure (g/kg-day) to the inorganic filler from occlusal surfaces; W_{oci} is the rate of wear (mm/day) for occlusal surface i ; AREA_{oci} is the area (mm^2) of occlusal surface i filled with composite resin; $\text{VOL}\%_{\text{inorgi}}$ is the percent by volume of inorganic filler in the composite resin in surface i ; $\text{DENSITY}_{\text{inorgi}}$ is the density (g/mm^3) of the inorganic filler in surface i ; and BW is adult body weight (kg).

$$\text{DOSE}_{\text{BIS-GMA-oc}} \text{ (g/kg-day)} = \sum_{i=1}^n (W_{\text{oci}} * \text{AREA}_{\text{oci}} * \text{VOL}\%_{\text{BIS-GMAi}} * \text{DENSITY}_{\text{BIS-GMAi}}) / \text{BW} \quad (2)$$

where, $\text{DOSE}_{\text{BIS-GMA-oc}}$ is the estimated exposure (g/kg-day) to the organic matrix from occlusal surfaces; $\text{VOL}\%_{\text{BIS-GMAi}}$ is the percent by volume of BIS-GMA in the composite resin in surface i ; $\text{DENSITY}_{\text{BIS-GMAi}}$ is the density (g/mm³) of BIS-GMA in surface i ; and other variables are as defined for equation (1).

$$\text{DOSE}_{\text{inorg-noc}} \text{ (g/kg-day)} = \sum_{i=1}^n (W_{\text{noci}} * \text{AREA}_{\text{noci}} * \text{VOL}\%_{\text{inorgi}} * \text{DENSITY}_{\text{inorgi}}) / \text{BW} \quad (3)$$

where, $\text{DOSE}_{\text{inorg-noc}}$ is the estimated exposure (g/kg-day) to the inorganic filler from non-occlusal surfaces; W_{noci} is the rate of wear (mm/day) for non-occlusal surface i ; $\text{AREA}_{\text{noci}}$ is the area (mm²) of non-occlusal surface i filled with composite resin; and other variables are as defined above.

$$\text{DOSE}_{\text{BIS-GMA-noc}} \text{ (g/kg-day)} = \sum_{i=1}^n (W_{\text{noci}} * \text{AREA}_{\text{noci}} * \text{VOL}\%_{\text{BIS-GMAi}} * \text{DENSITY}_{\text{BIS-GMAi}}) / \text{BW} \quad (4)$$

where, $\text{DOSE}_{\text{BIS-GMA-oc}}$ is the estimated exposure (g/kg-day) to the organic matrix from non-occlusal surfaces; and other variables are as defined above.

Research has demonstrated that BIS-GMA enzymatically degrades to release formaldehyde and methacrylic acid (Munksgaard and Freund 1990; Oysaed et al. 1988). Therefore, exposures to formaldehyde and methacrylic acid were calculated as follows:

$$\text{DOSE}_{\text{form}} \text{ (g/kg-day)} = \sum_{i=1}^n (\text{Area}_i * \text{PR}_{\text{formi}}) / \text{BW} \quad (5)$$

where $\text{DOSE}_{\text{form}}$ is the estimated exposure (g/kg-day) to formaldehyde from all occlusal and non-occlusal surfaces; Area_i is the surface area (mm²) of composite resin on surface i ; and PR_{formi} is the production rate (g/mm²/day) of formaldehyde from composite resin surface i on any given day.

$$\text{DOSE}_{\text{MA}} \text{ (g/kg-day)} = \sum_{i=1}^n (\text{Dose}_{\text{BIS-GMAi}} * \text{PR}_{\text{MAi}}) / \text{BW} \quad (6)$$

where $DOSE_{MA}$ is the estimated exposure (g/kg-day) to methacrylic acid from all occlusal and non-occlusal surfaces; $DOSE_{BIS-GMA_i}$ is the dose of BIS-GMA due to abrasive wear of surface i ; and PR_{MA_i} is the production rate ($\mu\text{g MA/mg polymer}$) of MA from the BIS-GMA released from composite resin surface i on any given day.

The leaching of unreacted methyl methacrylate from cured BIS-GMA has been reported but appears to be a short-lived process. Data of Thompson et al. (1982) and Tanaka et al. (1991) indicate that leaching of uncured monomer subsides in one to three days. As a result, this release will be insignificant to, and unrelated to, long-term daily exposures arising from wear and degradation processes. Therefore, leaching was not factored into estimates of long-term daily exposure.

Each composite-filled surface of a filled tooth was assumed to be independent of all other filled surfaces, reflecting the fact that the fillings placed in an individual's teeth are likely placed at different times, employing different materials, and reflecting variable skills of the dentist(s) and variable success of the filling placement.

In this assessment, Excel™ version 5.0 (Microsoft Corp. 1992) and Crystal Ball™ version 3.0.2 (Decisioneering Inc. 1993) were used to perform the dose calculations. 10,000 iterations were performed using a Monte Carlo simulation during which values for each variable were selected from probability density functions (PDF) of all possible or likely values for each variable. The characterization of each variable's PDF is tabulated in Table 1. A brief rationale for selecting each probability density distribution is discussed below.

Numbers of filled teeth

Unpublished data from the Nutrition Canada Survey (NCS; 1970-1972) describe the numbers of fillings in the mouths of 7161 Canadian adults aged 20+ years (Health Canada, unpublished data). Of these, 3045 adults had at least one filled tooth, and a maximum of 25 filled teeth. These data were used directly to produce a discrete probability distribution for adults with at least one filled tooth, shown in Figure 1. Note that exposure and risks were calculated only for the fraction of the population having filled teeth, and not for the Canadian population as a whole.

Although these data were collected between 1970 and 1972, they were considered reasonably representative of current Canadian occurrence of filled teeth in the population. More recent cross-sectional data on DMFT score (numbers of decayed, missing and filled teeth) in Canadian adults do not exist. However, the average numbers of filled teeth in the adult U.S. population in 1985-1986 was 9.05 (USDHHS 1987), a number comparable to the 8.23 filled teeth, on average, for Canadians aged 18 to 102 years with filled teeth (Health Canada, unpublished data). Therefore, the NCS data were employed to define this variable for all age groups.

For purposes of this assessment, all filled teeth were assumed to be filled with composite resin materials. Although only 10 to 20 percent of filled teeth in the Canadian population are currently composed of dental composite (based on 80% to 90% of fillings being dental amalgam (Richardson 1995)), the assumption of 100% of fillings being composite resin provides for the estimation of risks should all fillings be replaced with composite resin. This assumption also provides for the most equitable basis for comparison with risks posed by dental amalgam, for which all fillings were assumed to be composed of that material (see Richardson 1995).

Number of occlusal and non-occlusal surfaces per filling

Data relating to the number of surfaces per filling were reported by Nylander et al. (1987) for 25 cadavers. In the absence of any data more directly applicable to Canadians of all ages, these data were used to estimate the numbers of filled surfaces per filled tooth. Based on these data, a log-normal distribution was defined with an arithmetic mean of 1.64 ± 0.61 surfaces/filled tooth, minimum of 1 surface/filled tooth, and maximum of 5 surfaces/filled tooth.

The total number of occlusal surfaces could not exceed 16 in an adult, assuming only premolars and molars possess occlusal surfaces likely to be filled, and assuming the extraction of 3rd molars (wisdom teeth). One of the surfaces of a filled molar or premolar was always assumed to be the occlusal surface. Where the number of filled teeth was less than or equal to 16, these were always assumed to be molars or premolars. Where the number of filled teeth was less than or equal to 16, and there was only one filled surface per filled tooth, the single surface was always assumed to be an occlusal surface of a molar or premolar.

The number of non-occlusal surfaces (labio-lingual, mesio-distal) could not exceed 109 (4 non-occlusal surfaces for each of 16 molars and premolars, 5 non-occlusal surfaces for each of up to 9 remaining filled central, lateral and canine teeth).

Rates of wear of composite resins on occlusal and non-occlusal surfaces

Rates of wear of composite resin materials from occlusal surfaces were based on the review of El-Mowafy (1993) who compiled average abrasive wear measurements of 15 *in vivo* clinical studies of 9 different composite resin products. Based on these limited data, it was assumed that any value from 0.02 μm composite resin lost/day to 0.16 μm lost/day was equally likely.

Data on rates of wear for non-occlusal surfaces could not be located. However, Willems et al. (1993) reported that occlusal surfaces lacking opposing teeth (i.e., contact free) had a lower rate of wear than occlusal surfaces in contact with opposing teeth. Lacking data specifically on non-occlusal surfaces, it was assumed that the rate of wear of non-occlusal surfaces would be equivalent to that of contact-free occlusal surfaces. Based on the data reported by

Willems et al. (1993), contact-free surfaces wear at a rate ranging from 25% to 76% of the wear rate for occlusal surfaces with opposing teeth. Any value between this minimum and maximum was deemed equally likely.

Area of filled occlusal and non-occlusal surfaces

Areas of occlusal tooth surfaces were derived from data reported by Kraus et al. (1978) regarding the size of teeth. Assuming that the area of an occlusal surface approximated a rectangle, the area of occlusal surfaces of molars and premolars ranged from 52.5 mm² to 115.5 mm². The minimum size of an occlusal filling is unknown but was assumed to be 4 mm² for the purposes of this assessment. Therefore the filled area of any occlusal surface was assumed to range from 4 mm² to 115.5 mm², with any surface area between these values being equally likely.

Areas of non-occlusal tooth surfaces were also derived from data reported by Kraus et al. (1978) for the size of teeth. Assuming that non-occlusal surfaces are approximately rectangular in shape, then the area of non-occlusal surfaces ranges from 45.0 mm² to 89.25 mm². The minimum size of a non-occlusal filling is unknown but was assumed to be 4 mm² for the purposes of this assessment. Therefore, the filled area of a non-occlusal surface was assumed to range from 4 mm² to 89.25 mm², with any value in between being equally likely.

Volume percent of inorganic filler and BIS-GMA in composite resin

The precise volume percent of inorganic filler in a composite resin is product-dependent. Smith et al. (1993) reported that the inorganic filler in composite resin commonly ranges from 45% to 65% by volume. Therefore, it was assumed that any volume percent of inorganic filler between 45% and 65% was equally likely. The volume percent of BIS-GMA in composite resin was calculated as the difference between the volume percent of the inorganic filler and 100%.

Density of inorganic filler and BIS-GMA.

The density of SiO₂ (the only inorganic filler considered here) ranges from about 2.2 g/cm³ to 2.6 g/cm³ (2.2 x 10³ g/mm³ to 2.6 x 10³ g/mm³), depending on the physico-chemical nature of the final material (CRC 1994). As a result, it was assumed that the density of this inorganic filler would range between these upper and lower values, with any value in between being equally likely.

The density of the polymer BIS-GMA ranges from 0.99 g/cm³ to 1.1 g/cm³ (9.9 x 10⁻⁴ g/mm³ to 1.1 x 10⁻³ g/mm³) (D. Smith, University of Toronto, pers. com; S. Cannon, Canadian Dental Supply, pers. com.). Any value between these two limits was deemed equally likely.

Formaldehyde production rate from BIS-GMA

Oysaed et al. (1988) reported *in vitro* formaldehyde production at a rate ranging from approximately 0.05 µg to

0.3 µg formaldehyde/cm² of surface area of composite resin when the surface inhibition layer was removed. Production rate was dependent on the specific composition of the material. This production was measured after 72 hours, however, the majority of formaldehyde recovered was produced in the first 24 hours (Oysaed et al. 1988). Lacking more specific information on the rates of formaldehyde production *in vivo*, it was assumed that the formaldehyde production rate ranged between 0.05 µg/cm² and 0.3 µg/cm²/day, with any value in this range being equally likely.

Methacrylic acid production rate from BIS-GMA

Munksgaard and Freund (1990) reported *in vitro* methacrylic acid production from powdered composite resin under enzymatic hydrolysis at rates ranging from 0.06 µg to 0.1 µg methacrylic acid/mg polymer. Production of methacrylic acid appeared near complete after 400 minutes. Any polymer present in the oral cavity and gastrointestinal tract due to abrasive wear will be in the form of small particles, similar to the form (i.e., powder) tested by Munksgaard and Freund (1990). Passage through the gastrointestinal tract would involve more than 400 minutes (approximately 1440 minutes or 24 hours). Therefore, the data of Munksgaard and Freund (1990) were employed to define the rate of methacrylic acid production. This was assumed to range between 0.06 µg/mg and 0.1 µg/mg polymer, with any value in between being equally likely.

Adult body weight

In this assessment, body weights for adults were derived from the data of Stephens and Craig (1990), who reported data collected in 1988 on 2711 adults in Canada. These data were log-normally distributed with an arithmetic mean of 70.7 ± 14.5 kg. A log-normal probability density function with these characteristics was defined for this assessment.

3.0 RESULTS

Statistics and percentiles for estimated adult exposures to SiO₂, BIS-GMA, formaldehyde and methacrylic acid are presented in Table 2. Assuming that all fillings were composed of composite resin, and that the NCS data on numbers of filled teeth were representative of the current Canadian population, then mean estimated adult exposures were:

- 1) SiO₂ = 1.1 ± 0.88 µg/kg-day;
- 2) BIS-GMA = 0.41 ± 0.31 µg/kg-day;
- 3) formaldehyde = 0.020 ± 0.017 µg/kg-day; and
- 4) methacrylic acid = 3.3 × 10⁻⁵ ± 2.5 × 10⁻⁵ µg/kg-day.

4.0 REFERENCE DOSES FOR COMPONENTS AND DEGRADATION PRODUCTS OF COMPOSITE RESINS

There are no published reference doses for ingestion exposure to SiO₂ or to BIS-GMA and no studies were located regarding the chronic toxicity of these substances in animals following oral exposure.

In Canada, methyl methacrylate was unclassifiable with respect to carcinogenicity to humans (Chan et al. 1994). An ingestion reference dose for methyl methacrylate has been proposed by Health Canada of 53 µg/kg-day (Chan et al. 1994), based on decreased body weight and other effects observed in male and female hamsters and rats (EC/HC 1994). Methyl methacrylate is rapidly metabolized, first by hydrolysis to methacrylic acid and then, via other mechanisms, primarily to carbon dioxide (EC/HC 1994). Due to this rapid metabolism, systemic effects associated with methyl methacrylate exposure are likely due to methacrylic acid or another metabolite, and not methyl methacrylate *per se*. As a result, the reference dose of methyl methacrylate can be applied for assessment of risks posed by exposure to its hydrolysis product, methacrylic acid.

The toxicity of formaldehyde has been extensively investigated and assessed by the U.S. EPA (IRIS 1995). The U.S. EPA has established an ingestion reference dose of 200 µg/kg-day, based on a study reporting reduced weight gain in rats, as well as histopathological changes in the gastrointestinal tract, after chronic ingestion of formaldehyde in drinking water (see Til et al. 1989). An uncertainty factor of 100 (10 for intraspecies variation, 10 for interspecies extrapolation) was applied to a no-observed-adverse-effect level (NOAEL) of 15 mg/kg-day in male rats (with rounding to give the prescribed reference dose).

5.0 DISCUSSION AND RISK CHARACTERIZATION

SiO₂ is virtually insoluble in water and acids (CRC 1994). Therefore, particles of this material will not dissolve in the gastrointestinal tract and will not likely be systemically absorbed. As a result, it represents little or no risk. This may not be true, however, for other inorganic fillers which may contain boron (borosilicate glass), ytterbium-fluoride, or other elements. These alternate inorganic fillers require assessment on a product-specific basis.

Estimated exposure to formaldehyde, as a result of the enzymatic degradation of composite filling surfaces, was many times less than the reference dose prescribed by the U.S. EPA. Mean estimated exposure (0.020 µg/kg-day) was 10,000 times less than the U.S. EPA reference dose, whereas the maximum estimated exposure of 0.15 µg/kg-day

was 1333 times less than the reference dose.

Methacrylic acid exposure estimated from the enzymatic degradation of ingested BIS-GMA particles, was also far less than the reference dose prescribed by Health Canada. Mean exposure was more than 1,600,000 times below the reference dose of 53 µg/kg-day, and the maximum exposure was more than 230,000 times below the reference dose.

No reference dose or chronic ingestion study could be located for BIS-GMA. As a result, the risks of exposure to this substance from composite dental restorations can not be directly assessed. However, it is anticipated that particles of this polymer would not be absorbed from the gastrointestinal tract. The more likely risk from BIS-GMA is posed by its enzymatic degradation to methacrylic acid (Munksgaard and Freund 1990) and formaldehyde (Oysaed et al. 1988). To assess the maximum possible risk posed by these degradation products it was further assumed that 100% of the BIS-GMA released into the mouth and gastrointestinal tract, as a result of abrasive wear, was metabolized to the equivalent mass of methacrylic acid, and then of formaldehyde.

The mean estimated exposure to BIS-GMA was 0.41 µg/kg-day, whereas the maximum estimated exposure (100th percentile) to this substance in adults with composite resin fillings was 2.83 µg/kg-day (see Table 2). Assuming all BIS-GMA was metabolized to an equivalent mass of methacrylic acid, then the mean estimated exposure would be 129 times lower than the prescribed reference dose of 53 µg/kg-day, and the maximum estimated exposure would be 19 times less than this reference dose.

Likewise, to assess the maximum likely risk posed by formaldehyde, as a degradation product of BIS-GMA, it was assumed that 100% of the BIS-GMA released into the mouth as a result of abrasive wear was metabolized to the equivalent mass of formaldehyde. This mass of metabolite was compared to the reference dose for formaldehyde derived by the U.S. EPA of 200 µg/kg-day. Assuming all BIS-GMA was converted to formaldehyde, then the mean estimated exposure would be 488 times lower than the prescribed reference dose, and the maximum estimated exposure would be 71 times less than the reference dose.

It is unlikely that BIS-GMA would be completely metabolized to an equivalent mass of either methacrylic acid or formaldehyde. Therefore, the worst case exposures suggested above for these two metabolites will have over-estimated actual exposures and subsequent risks.

6.0 CONCLUSIONS

Based on the foregoing analysis, it was concluded that composite resin dental restorations containing silica as the inorganic filler present no appreciable risk with respect to long-term daily exposure to SiO₂, formaldehyde or methacrylic acid.

No data on the chronic toxicity of BIS-GMA in animals or humans were located. These data are necessary before the full risks of these materials can be completely assessed. Although *in vitro* data exist demonstrating the leaching of methyl methacrylate out of set composite resin, this leaching is short-lived, lasting perhaps 1 to 3 days. However, *in vivo* data are required on the rate of leaching of unreacted methyl methacrylate out of set composite resin fillings to confirm this short duration, and to quantify levels of potential exposure.

7.0 CLOSURE

The foregoing report summarizes the results of a study to assess the exposure and risks associated with the components and degradation products of composite resin dental materials. We trust that the information presented in this report is satisfactory for your requirements. Should you require additional information or clarification, please contact the undersigned.

Respectfully submitted,
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Table 1. Summary of probability density functions for variables employed in the assessment of exposure and risks to components and degradation products of composite resin dental materials.

Variable	PDF characterization
No. filled teeth	Custom; see Figure 1
No. filled surfaces per filled tooth	LN ^a : 1.64 ± 0.61; min=1, max=5
Rate of wear of occlusal surfaces (µm/day)	U ^b : 0.02 - 0.16
Rate of wear of non-occlusal surfaces (% of rate for occlusal surface)	U: 25 - 76
Area of occlusal surfaces (mm ²)	U: 4.0 - 115.5
Area of non-occlusal surfaces (mm ²)	U: 4.0 - 89.25
Volume % inorganic filler (SiO ₂) (%)	U: 45 - 65
Density of SiO ₂ (g/cm ³)	U: 2.2 - 2.6
Density of BIS-GMA (g/cm ³)	U: 0.99 - 1.10
Formaldehyde production rate (µg/cm ² surface area)	U: 0.05 - 0.3
Methacrylic acid production rate (µg/mg polymer)	U: 0.06 - 0.10
Adult body weight (kg)	LN: 70.7 ± 14.5

^a LN= log-normal distribution; values are arithmetic mean ± standard deviation, minimum, maximum (if applicable). ^b U = uniform distribution; values represent minimum and maximum.

Table 2. Statistics and percentiles of dose estimates for silica, BIS-GMA, formaldehyde and methacrylic acid from composite resin dental materials.

Statistic	SiO ₂	BIS-GMA	formaldehyde	methacrylic acid
	(µg/kg-day)	(µg/kg-day)	(µg/kg-day)	(µg/kg-day)
Mean	1.14	0.41	0.020	3.3E-05
Standard Deviation	0.88	0.31	0.017	2.5E-05
Percentiles: 5%	0.10	0.04	0.002	2.8E-06
10%	0.17	0.06	0.003	4.9E-06
20%	0.35	0.12	0.006	9.9E-06
30%	0.54	0.20	0.009	1.5E-05
40%	0.75	0.27	0.012	2.1E-05
50%	0.97	0.35	0.016	2.8E-05
60%	1.21	0.43	0.020	3.5E-05
70%	1.49	0.53	0.025	4.3E-05
80%	1.83	0.65	0.032	5.2E-05
90%	2.33	0.83	0.043	6.6E-05
95%	2.78	0.99	0.053	7.9E-05
maximum	8.01	2.83	0.153	2.3E-04

Figure 1. Occurrence of filled teeth in adults (aged 20+ years). From the Nutrition Canada Survey (Health Canada, unpublished data).