ISSN 0973-2063 (online) 0973-8894 (print)
Bioinformation 22(10): 7034-7038 (2026)
©Biomedical Informatics (2026)

www.bioinformation.net
Volume 22(10)

Review

Received October 1, 2026; Revised October 31, 2026; Accepted October 31, 2026, Published October 31, 2026

DOI: 10.6026/973206300227034

SJIF 2026 (Scientific Journal Impact Factor for 2026) = 8.478
2022 Impact Factor (2023 Clarivate Inc. release) is 1.9

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Edited by Ruby Singh
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Citation: Gilhotra *et al*. Bioinformation 22(10): 7034-7038 (2026)

Toxicity of amalgam and composite restorations: A review

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ISSN 0973-2063 (online) 0973-8894 (print)
Bioinformation 22(10): 7034-7038 (2026)
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Abstract:
Dental amalgam and resin composite are the most widely used direct restoratives, yet neither is chemically inert in the mouth. Therefore, it is of interest to compare the toxicological evidence, focusing on wear dependent mercury release and the dietary and physicochemical factors that drive monomer elution. Amalgam contains roughly 50% elemental mercury, a recognised neurotoxicant now phased down under the 2013 Minamata Convention. Composites continuously elute residual monomers such as BisGMA, TEGDMA, UDMA and HEMA for days to weeks after placement. Regulators conclude that population exposure stays below disease-causing levels, but vulnerable subgroups and chronic low-dose effects remain understudied, making this gap itself the basis for caution.

Keywords: Dental amalgam, resin composite, mercury, monomer elution, BisGMA, bisphenol A, biocompatibility

Background:
Direct tooth restoration has relied for over a century on two broad classes of material: metallic amalgam and more recently, resin-based composite **[1]**. Amalgam is an alloy formed by mixing liquid mercury (approximately 50% by weight) with a powder of silver, tin, copper and sometimes zinc; its mechanical durability and low cost made it the material of choice through most of the twentieth century, but its mercury content has driven a global phase down, particularly following the 2013 Minamata Convention on Mercury **[2]**. Mercury is a well-established toxicant with documented neurological, renal, respiratory and haematological effects at sufficient absorbed dose and amalgam remains a continuous source of elemental mercury for much of the population carrying such restorations **[3]**. Resin composites replace the metallic matrix with a cross-linked polymer of dimethacrylate monomers reinforced with inorganic filler and are frequently perceived by patients as the safe, biocompatible, mercury free alternative **[4]**. However, polymerisation in the mouth is never complete: conversion of monomer to polymer typically reaches only 45-75%, leaving a fraction of unreacted, low molecular weight, bioactive monomer trapped in the matrix **[5]**. This residual monomer, together with degradation products formed as the resin hydrolyses over time, is released into saliva and can reach the gastrointestinal tract and systemic circulation and meta-analysis has attempted to quantify the order of magnitude involved **[6]**. Therefore, it is of interest to compare the toxicological profiles of the two material classes, with specific attention to the dietary and physicochemical variables that modulate release and to evaluate whether either can reasonably be described as biologically inert.

Dental amalgam: mercury release and systemic uptake:
Amalgam releases mercury by two parallel routes: evaporation of elemental mercury vapour from the restoration surface and mechanical or chemical release of particulate and ionic mercury during chewing, tooth-brushing, bruxism and corrosion. The rate is not fixed - it rises with the number and surface area of fillings, occlusal load, parafunctional habits and consumption of hot, acidic or abrasive food and drink, all of which increase wear or corrosion **[5].** Modern high-copper amalgams are less stable than older formulations: when polished or worn they form mercury rich surface droplets and emit substantially more mercury vapour, confirming that release is a dynamic, mechanically modulated process rather than a fixed background rate **[6]**. The physicochemical determinants of release for both materials are compared in **(Table 2).** Human studies confirm that amalgam mercury is systemically absorbed. Following complete removal of all amalgam fillings, subjects showed elevated mercury in saliva, plasma, urine and faeces that declined only gradually, with plasma mercury still near 40% of baseline 60 days after removal **[6]**. The same body of work documented an increase in the proportion of intestinal bacteria resistant to mercury and to antibiotics after amalgam placement and removal, indicating a measurable biological interaction between released mercury and the gut microbiome **[7]**. Despite this documented absorption, the consensus of major regulatory bodies is that the low levels of mercury vapour released by intact restorations have not been proven, in epidemiological studies, to cause systemic disease in the general population and that available data do not support routine removal of sound fillings. These bodies nonetheless flag certain subgroups pregnant women, young children and individuals with pre-existing renal or neurological vulnerability or a genuine mercury allergy as meriting precaution and acknowledge that the evidence base is limited by small samples and short follow-up **[8]**. The regulatory positions and their acknowledged limitations are summarised in (**Table 5).**

Table 1: Comparative toxicological profile of amalgam and resin composite restorations

Parameter	Dental amalgam	Resin composite
Primary toxicant of concern	Elemental and inorganic mercury (vapour and particulates)	Unreacted/leachable monomers (BisGMA, TEGDMA, UDMA, HEMA) and additives (BPA, camphorquinone)
Release mechanism	Corrosion, evaporation and mechanical abrasion during chewing, brushing and bruxism	Incomplete polymerisation (45–75% conversion) with hydrolytic and enzymatic degradation of the matrix
Exposure profile	Continuous, low-level, for the life of the restoration (years–	Highest in the first 24–48 h, then intermittent and diet-modulated;

	decades)	reactivated by wear/repair
Documented biological effects	Elevated urinary/blood/plasma mercury; antibiotic- and mercury-resistant oral/gut flora	Cytotoxicity and genotoxicity in vitro; oxidative stress; cytokine dysregulation; BPA-linked endocrine activity
Consensus position	No proven population-level systemic disease from intact fillings; vulnerable groups flagged	No composite withdrawn on toxicological grounds; in-vivo human data remain limited

BPA, bisphenol A. Positions reflect current regulatory and professional consensus rather than proof of safety.

Table 2: Physicochemical and dietary factors that modulate release from each material

Factor	Effect on amalgam	Effect on resin composite
Low pH (acidic food/drink)	Promotes surface corrosion and ionic mercury release	Hydrolyses ester linkages; increases water sorption and monomer leaching
Ethanol / alcohol	Limited direct effect	Swells the polymer network; elutes several-fold more BisGMA/TEGDMA/HEMA
Elevated temperature	Increases mercury vapour evaporation	Increases diffusion and softening of the matrix
Mechanical load / wear	Forms mercury-rich droplets; raises vapour after chewing/polishing	Exposes fresh, unweathered material; sustains monomer release

Diet and oral-hygiene behaviour therefore influence real-world exposure from both materials.

Table 3: Documented biological effects reported for each material

Level	Dental amalgam	Resin composite
Cellular / molecular	Cytotoxicity of mercury compounds in cultured human cells	DNA strand breaks, genotoxicity, oxidative stress and apoptosis from eluted monomers
Immune / inflammatory	Interaction with oral and gut microbial resistance	Altered cytokine secretion (IL-1β, TNF-α) in stimulated leukocytes
Human / systemic	Raised mercury in saliva, blood, urine and faeces after exposure	Free monomer detectable in saliva, urine and blood; toxicity reported as relatively low

In-vitro potency is generally greater for BisGMA and UDMA than for the more hydrophilic HEMA and TEGDMA.

Table 4: Resin-composite monomers and additives of toxicological interest

Component	Role in the material	Toxicological note
BisGMA	High-molecular-weight base monomer	Genotoxic in vitro; BPA is a precursor/degradation product
UDMA	Base/diluent monomer	Cytotoxic and pro-apoptotic at sub-lethal doses
TEGDMA	Low-viscosity diluent co-monomer	Highly mobile; readily eluted; mutagenic in vitro
HEMA	Hydrophilic co-monomer/adhesive component	Water-soluble; induces oxidative stress and apoptosis
Camphorquinone / BPA	Photo-initiator / degradation product	Additive leachables; BPA raises endocrine concern

BisGMA, bisphenol A-glycidyl methacrylate; UDMA, urethane dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; BPA, bisphenol A.

Table 5: Regulatory/consensus positions and acknowledged evidence limitations

Aspect	Current position	Acknowledged limitation
General population	Exposure from intact restorations not proven to cause systemic disease	Short follow-up; reliance on surrogate biomarkers
Sound fillings	Routine removal not recommended	Removal itself transiently raises mercury exposure
Vulnerable subgroups	Precaution advised for pregnant women, young children and susceptible individuals	Cumulative and long-term low-dose effects incompletely studied

'Insufficient evidence of harm' is not equivalent to 'confirmed evidence of safety'.

Resin composite: monomer elution and its modifiers:

Composite resins are built around a dimethacrylate matrix - commonly BisGMA, UDMA and TEGDMA, sometimes with the more hydrophilic HEMA - polymerised by a free-radical reaction initiated by visible light and a photo-initiator such as camphorquinone. Because chain growth is limited by mobility restrictions within the setting matrix, the degree of conversion rarely reaches 100%, so unreacted monomer, oligomers and additives (including trace bisphenol A) remain embedded in the cured material and are released progressively, both immediately after curing and later as the network undergoes hydrolytic and enzymatic degradation **[9]**. Newer low shrinkage and BPA-free resin chemistries are being developed to reduce this residual burden, although conventional dimethacrylate systems remain the most widely used **[10]**. The principal monomers and additives of concern are listed in **(Table 4).** A substantial experimental literature has quantified how the chemical environment of the mouth modulates release. Ethanol and methanol based solvents elute several-fold higher concentrations of BisGMA, TEGDMA, HEMA and BPA than water, because the solubility parameter of ethanol closely matches that of BisGMA and allows the solvent to swell the network and draw out unreacted monomer; a 75% ethanol/water mixture is used experimentally precisely because it accelerates, within hours, degradation that would otherwise occur over months, which has direct relevance to alcohol-containing mouthwashes and beverages **[11, 12]**. Chromatographic studies identifying the organic eluates confirm that the released fraction includes monomers, initiators, stabilisers and degradation products rather than a single compound **[13, 14]**. Low environmental pH from acidic foods and cariogenic acids hydrolyses the ester linkages of BisGMA, TEGDMA and UDMA - a process catalysed by salivary esterases while elevated temperature and mechanical wear further increase diffusion and expose fresh material **(Table**

2). Among the additives, bisphenol A, a hydrolysis and degradation product, is of particular concern owing to its endocrine activity and has been measured from some materials **[13]**. Eluted monomers are biologically active in laboratory models. Components leached from cured composites induce DNA double-strand breaks in primary human gingival fibroblasts **[15, 16]** and monomers such as TEGDMA and HEMA are genotoxic causing gene mutations, micronuclei and strand breaks and delaying the cell cycle **[17, 18]**. At sub-lethal doses, BisGMA, UDMA and TEGDMA also alter apoptosis and cytokine secretion (IL-1β, TNF-α) in human leukocytes challenged with a periodontal pathogen **[17]**. Detectable free monomer has been measured directly in patient saliva, urine and blood after composite placement; a recent systematic review of *in vivo* human studies characterised the resulting local and systemic toxicity as relatively low while cautioning that existing detection methods have important limitations and that further study is required **[19]**. These documented biological effects are compared across the two materials in (**Table 3).**

Comparative analysis:

(Table 1) summarises the parallel toxicological pathways of the two material classes. Both share a common pattern: a chemically active substance mercury in one case, monomer and additive residue in the other is incorporated into a solid restoration that is nonetheless not fully inert and is released into the oral cavity and systemic circulation at a rate that is measurable, biologically active in laboratory models and modulated by mechanical, thermal and chemical conditions the patient controls only partly **[20]**. The two exposure profiles differ in shape. Mercury release from amalgam is essentially continuous for the working life of the restoration, which may span decades, with cumulative absorption reflected in blood, urine and faecal mercury that persists for months even after the source is removed **[21]**. Composite monomer release is highest in the first 24–48 hours after placement or repair and then declines, but is never reduced to zero, because hydrolytic and enzymatic degradation continues for as long as the restoration is exposed to saliva, food and drink so elution is repeatedly reactivated each time the restoration is polished, repaired, or mechanically or chemically stressed. *In vitro* work that directly compares composite components with mercury compounds confirms that both classes are cytotoxic to human cells, differing in kind rather than in the mere presence of biological activity **[22, 23]**. In this sense, amalgam represents chronic low-level exposure to a single, well-characterised heavy metal, whereas composite represents intermittent, diet-dependent exposure to a mixture of organic monomers and additives whose combined long-term systemic effect in humans is comparatively less well characterized **[24, 25].**

Conclusion:

Dental amalgam and resin composite both release measurable substances during clinical use. Current evidence does not conclusively establish either material as entirely free of biological effects. Further long-term clinical studies are needed to guide evidence based material selection.

Declarations:

Funding: The authors received no specific funding for this work.

Conflicts of interest:

The authors declare that they have no competing interests.

Ethical approval:

Not applicable; this is a narrative review of previously published literature and did not involve human participants, animals or identifiable patient data.

Author contributions:

V. Gilhotra - conceptualization, literature search, data interpretation, manuscript drafting and revision; A. Chhabra - supervision, critical revision and final approval; A. Sarkar - literature review, editing and critical review; Shilpa R, A. Banerjee and Shraddha - literature search and manuscript review. All authors have read and approved the final manuscript.

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