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Toxic effects of mercury in dental amalgam

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Abstract
Dental amalgam is a dental restorative material that has been used in dentistry for over 150 years. Dental amalgam consists of an alloy powder containing silver, copper, tin, and other trace metals, providing strength and durability to dental restorations. Furthermore, its liquid component, elemental mercury, ensures the proper handling and manipulation of the alloy during placement. Throughout its history, dental amalgam has undergone significant advancements in alloy composition. Today, the most widely used dental amalgam alloys are the high copper-tin alloys, which offer superior performance and longevity. These high copper-tin alloys have proven to be highly successful in dental restorations due to their enhanced physical properties, such as improved strength, resistance to corrosion, and reduced creep.
The specific composition of dental amalgam alloys determines their classification. Alloys containing greater than 12% tin are known as low-copper, while those containing less than 12% tin are recognized as high-copper alloys. This categorization plays a crucial role in determining the properties of the dental restorations created with these alloys. Although the high copper dental alloys were scientifically introduced in 1963, it took time before they gained widespread acceptance and became the standard alloy used in most countries. It wasn't until the late 1970s that these high-copper alloys became the norm in dental practice. Their popularity can be attributed to extensive research, clinical trials, and advancements in dental technology, which ultimately led to their recognition as the superior choice for dental restorations.

Keywords: Dental amalgam, mercury, physical properties

1. Introduction
Dental amalgam remains an indispensable material in dentistry, providing a cost-effective and reliable solution for restoring teeth affected by decay, fractures, or other dental conditions. Its longevity, strength, and biocompatibility make it a preferred choice for many dental professionals worldwide. Moreover, ongoing research and development in dental materials continue to enhance the properties and performance of dental amalgam, ensuring its continued relevance and effectiveness in modern dental practice. (Gallusi *et al*. 2021) [1] (Schmalz & Widbiller, 2022) [2] (Ajiboye *et al*. 2020) [3] (Dudeja *et al*., 2023) [4].
Due to the numerous advantages of dental amalgam, it continues to be the most widely used material in dentistry. Dental amalgam is inexpensive, easy to manipulate, and exhibit excellent strength and durability when placing a restoration. Moreover, several studies indicate that freshly placed dental amalgam restorations withstand wear better than any other material currently available. It is worth mentioning that dental amalgam's popularity is reflected in its annual use, which amounts to approximately 3000 and 700 hundred tons per year in the United States and the world respectively. Considering its resilience, dental amalgam restorations are widely recognized for their ability to survive in the oral cavity for over two decades, making them a long-lasting option for patients. However, despite the many advantages provided by dental amalgam restorations, recent studies have raised concern regarding the potential environmental hazards associated with metallic mercury. In particular, breast milk has been identified as a significant route of exposure to mercury for very young infants, and dental amalgam is believed to be the most probable secondary source of this mercury present in breast milk. This concern highlights the importance of further investigating and understanding the potential risks associated with the use of dental amalgam in order to ensure the safety and well-being of patients. Therefore, while dental amalgam undoubtedly presents numerous

advantages, it is crucial to address any potential environmental and health concerns related to its use through ongoing research and education. (Jirau-Colón *et al*., 2019) [5] (Moxon, 2024) [6] (Mahalaxmi, 2020) [7] (Annar, 2022) [8].

1.1 Composition and Usage

Dental amalgam, a widely used dental restorative material for over 150 years, is an alloy of metals containing mercury as one of its components. Dental amalgams contain metallic alloy particles (usually a combination of silver, tin, copper, and zinc) mixed with liquid mercury. When triturated, microscopic alloy particles are coated with mercury, and together they form a pliable mass that can be easily packed into a cavity preparation. The mixture is then carefully carved and sculpted in order to restore the original shape and contour of the tooth, ensuring a seamless integration with the surrounding dental structures. This process requires precision and skill, as the dentist meticulously works to recreate the natural anatomy and aesthetics of the tooth, guaranteeing both functionality and visual appeal. By utilizing their expertise and knowledge of dental materials, dentists are able to achieve durable and long-lasting restorations that provide patients with the confidence to smile brightly and chew comfortably. (Dudeja *et al*., 2023) [4] (Moxon *et al*., 2023) [9].

Commonly used in posterior teeth and high-stress areas due to its strength and durability, dental amalgam accounts for over 50% of applied restorative materials, particularly among children. Although the Food and Drug Administration (FDA) considers it a “safe and effective” restoration option, it is crucial to be aware of the potential health risks associated with dental amalgam. The main concern lies in the fact that amalgam's primary component is mercury, which poses a toxic threat to oral health. Amalgam toxicity can occur due to the liberation of mercury vapor before and after placement, as well as the leaching of soluble organic compounds from the amalgam restoration. Furthermore, the demineralization leaching element, such as mercury, is more likely to occur during the acid challenge. To fully comprehend the potential pathways through which toxicity may arise from dental amalgam, it is essential to understand its constituents and their effects on oral health. (Jirau-Colón *et al*., 2019) [5] (Aftabi *et al*. 2021) [10].

1.2. Historical Perspective

And reducing the need for more extensive dental interventions. In addition to its durability, dental amalgam is also highly biocompatible, meaning that it is well-tolerated by the oral tissues and does not induce any adverse reactions.

The process of placing a dental amalgam filling involves several steps. First, the dentist prepares the affected tooth by removing the decayed tissue and shaping the cavity to maximize the retention of the filling. Then, the dentist mixes the powdered metal alloy with liquid mercury to form a pliable mass. This mass is carefully packed into the prepared cavity, ensuring that it completely fills the space and conforms to the natural contours of the tooth. Once in place, the dental amalgam undergoes a chemical reaction known as amalgamation, where the mercury binds with the metal atoms to create a solid, durable filling material. Over time, the dental amalgam undergoes minor changes due to galvanic reactions with other metals in the mouth. While these changes are usually harmless, they can occasionally lead to discoloration of the filling or a metallic taste. However, modern dental amalgam formulations have greatly reduced the occurrence of these side effects. Despite its effectiveness and long history of use, dental amalgam has faced some controversy in recent years. This is mainly due to concerns about the potential health risks associated with exposure to mercury, which is a component of dental amalgam. However, numerous well-conducted scientific studies have consistently found that the level of mercury released from dental amalgam fillings is very low and does not pose a significant risk to human health. Additionally, various dental organizations and regulatory bodies around the world, including the World Health Organization, American Dental Association, and European Union, have all affirmed the safety and efficacy of dental amalgam as a restorative material. In conclusion, dental amalgam is a time-tested and reliable dental restorative material that plays a crucial role in the prevention and treatment of dental caries. Its affordability, durability, and biocompatibility make it a preferred choice for tooth fillings. While concerns exist regarding the presence of mercury, the scientific consensus supports its safety and effectiveness. With proper oral hygiene and regular dental care, individuals can maintain their dental health and preserve their natural teeth with the help of dental amalgam fillings. (Berlin, 2020) [11] (Tuček *et al*. 2020) [12] (Geier & Geier, 2022) [13] (Dudeja *et al*., 2023) [4]. Dental amalgam has remained a fundamental restorative material in dentistry since its inception. Although the practice of amalgam was introduced in 1816, its dental applications have been controversial since the 1830s and increasingly so in the 21st century. However, despite the controversy, amalgam was used extensively in the 1960s. William A. Bailey’s “treatise” in 1835 describing the clinical procedures and rationales for using it aided in prompting “the amalgam era.” Following Bailey’s treatise, a number of dental schools incorporated amalgam fillings in their curricula, thereby establishing the use of amalgam in the United States (Jirau-Colón *et al*., 2019) [5].

2. Mercury Toxicity

Mercury is a silver-white metal, but it is also the only metal that is liquid when at ordinary temperature conditions. It is a good thermal conductor and is able to conduct electricity, thus making it a good constituent for the dental restorative material known as dental amalgam. Dental amalgam consists of a mixture of liquid mercury and metal alloy powder. Silver (Ag), tin (Sn), copper (Cu), and zinc (Zn) in the form of metal powder alloy are mixed with liquid mercury to react chemically and hardened dentin-like material is formed. Dental amalgam has been used as a dental restorative material for over 150 years and it is still one of the most widely used materials in dentistry, as it is cost-effective, easy to use, and durable. However, in the mouth, it is not an inert material. There are continuous leaching and corrosion products of both silver and mercury, and it is mainly mercury which is leached from amalgams in the oral cavity. Once in solution, mercury can cross a variety of biological membranes and reach the systemic circulation. That is, mercury vapor released from dental amalgams can be inhaled into the lungs. This not only produces exposure to the central nervous system but also leads to the introduction of mercury into the general circulation with the formation of blood–mercury complexes that can be rapidly distributed throughout the body. Mercury has been implicated in the etiology of several diseases and this article deals with the potential toxicity of this metal and its action on biological systems, with a special focus on its possible side effects on the oral cavity. The potential risk of mercury from dental amalgam restorations are also discussed.

Mercury vapor exposure has been a topic of concern in the field of dentistry for many years, and its potential risks on human health continue to be evaluated. It is important to note that the majority of research conducted on this subject suggests that the levels of mercury released by dental amalgam restorations are relatively low and not considered harmful in most cases. However, there are certain populations, such as pregnant women, children, and individuals with specific health conditions, who may be more susceptible to the effects of mercury exposure. Studies have shown that prolonged exposure to high levels of mercury can lead to adverse health effects, including neurological disorders, kidney damage, and cardiovascular problems. The central nervous system is particularly vulnerable to the toxic effects of mercury, as it can easily cross the blood-brain barrier and accumulate in brain tissues. This can result in cognitive impairments, memory loss, and even behavioral changes. In addition to its potential effects on the central nervous system, mercury can also have harmful effects on the oral cavity itself. Studies have suggested that dental amalgam restorations may contribute to the development of oral health issues, such as gum inflammation, oral lichen planus, and changes in the composition of oral microbiota. However, it is important to note that these studies are still inconclusive, and further research is needed to establish a definitive link between dental amalgam and these oral health conditions.

Despite the concerns surrounding mercury, dental amalgam continues to be widely used in dentistry due to its durability, cost-effectiveness, and ease of use. However, alternative restorative materials, such as composite resins and ceramics, have gained popularity in recent years as they do not contain mercury and offer aesthetic advantages. In conclusion, while dental amalgam has been a reliable and effective dental restorative material for many years, it is important to consider the potential risks associated with mercury exposure. Dentists and patients alike should be aware of the potential side effects and make informed decisions regarding the use of dental amalgam restorations. Further research is needed to better understand the long-term effects of mercury exposure and to develop safer alternatives for dental restorations. (Dudeja *et al*., 2023) [4] (Jirau-Colón *et al*., 2019) [5].

2.1. Chemical Properties of Mercury

Essential knowledge of the chemical properties of mercury is crucial to understand the complex mechanisms of its toxicity. In order to grasp the full extent of its effects, it is essential to delve into the various aspects and intricacies of this relatively rare element that exists in our Earth's crust. Mercury, having a minuscule presence of only 0.08 parts per million, can be found in exceedingly small amounts within a diverse range of minerals. One of the most prominent naturally occurring minerals where mercury is mined is alsace (HgS). Additionally, there are other notable minerals such as calomel (Hg2Cl2), fritillaria (Hg2Sb2S5), galli (HgAg2S), and torrasite (Hg2InV2O8) that contain this fascinating element.

To truly comprehend the impact of mercury on our planet, it is imperative to recognize the ways in which it is released into our environment. Fusion reactions and volcanic eruptions play a significant role in the dispersion of this element into the biosphere and hydrosphere. Following its release, mercury undergoes intricate biogeochemical cycles, undergoing transformation from inorganic mercury to methylmercury (MeHg) facilitated by various microorganisms. This transformation is not only crucial but also introduces another layer of complexity to the understanding of mercury's behavior and its potential consequences. Through these intricate processes, mercury bio accumulates in the food chain, gradually magnifying its presence and impact on various organisms. This bioaccumulation poses significant risks as it leads to heightened concentrations of mercury in the organisms higher up the food chain, including humans. Thus, a comprehensive understanding of the properties, behaviors, and transformations of mercury is paramount in order to effectively address the potential hazards associated with its exposure. By expanding our knowledge of the chemical properties of mercury, we are better equipped to navigate the complexities of this enigmatic element. This expanded understanding will ultimately contribute to the development of effective strategies for mitigating its toxic effects and ensuring the preservation of our environment and the health of all living organisms. (Mao *et al*. 2021) [14] (Kumar *et al*. 2023) [15] (Zafar *et al*. 2024) [16] (Dudeja *et al*., 2023) [4], (Jirau-Colón *et al*., 2019) [5]. Mercury is a highly versatile and dynamic polymorphic metal that exhibits various forms. Among these forms, the most prevalent and stable is the renowned ß-mercury, which showcases a remarkable hexagonal close-packed structure. With fascinating properties, it boasts a melting point of -38.83 °C and a boiling point of 357 °C, distinguishing itself as a metal with an impressive range of applications. Furthermore, it is noteworthy that ß-mercury possesses the highest density among all metals, measuring at a staggering 13.596 g/scc.

In its elemental state, mercury manifests as a captivating bright liquid with a silvery appearance. At room temperature, it undergoes intriguing transformations, expanding when subjected to heat and contracting upon cooling. Such responsiveness to temperature variations contributes to its exceptional attributes and applications in various fields.

Despite its compelling characteristics, it is noteworthy that mercury stands unique among metals due to its peculiar behavior towards glass and porcelain surfaces. Unlike most metals, mercury exhibits a fascinating quality of not wetting glass or porcelain. This exceptional feature allows for the formation of a break within mercury columns employed in barometers or thermometers, enhancing the accuracy and reliability of these instruments. However, it is essential to exercise caution with this mesmerizing metal. When a piece of mercury is unleashed without obstruction, it has a tendency to fragment into small beads and spontaneously roll away. In the event such beads are discovered, they must be promptly collected using appropriate gloves to minimize any potential risks. Moreover, it is crucial to ensure the immediate cleaning of the area where the mercury was present, employing wet mops to effectively remove any residual traces. This is crucial as mercury is not only a captivating substance but also a serious pollutant that can have detrimental effects on the environment and human health. (Colomban 2021) [17] (Colomban 2021) [18].

2.2. Routes of Exposure

Mercury can enter the human body through various routes: inhalation, skin contact, ingestion, and efficiently penetrating the blood-brain barrier and placenta. Elemental mercury is a highly potent toxin, even more harmful than methylmercury. Common sources of mercury exposure include fish consumption, dental amalgams, mercury-dependent industry discharges (Such as mining and mercury bridge activities, as well as chlor-alkali factories), waste incinerators, and skin-lightening creams. Mercury is universally dispersed in the environment, particularly in water and air, potentially impacting human health in profound ways. Exposure to mercury can occur frequently, acutely, or subacutely over a span of a few days. Dental amalgam remains one of the most prevalent avenues for individuals to come into contact with mercury. Even if exposure occurs at low levels, continuous exposure for extended periods, spanning many years, can have detrimental effects on human health. (Miriam Varkey *et al*., 2015) [19]. Methylmercury can readily accumulate in the tissues of various fish species, ultimately making its way up the food chain and posing potential risks to human health. Thus, it is crucial to acknowledge that fish consumption serves as an indirect source of exposure to methylmercury through dietary intake. Additionally, it is worth noting that fish consumption is just one facet of human exposure to mercury, as dental amalgam also plays a significant role in introducing both organic (MeHg) and inorganic Hg into individuals. For more than a century, dental amalgam has been widely utilized as a dental restorative material by dentists across the globe. This amalgamation consists of a carefully measured blend of metals, including liquid mercury, silver, tin, copper, and zinc. Such a formulation ensures the creation of a durable and long-lasting dental filling. In line with the ADA/ANSI/ISO specification no. 108 from 1990, it is essential to note that any dental amalgam alloy must contain specific proportions by weight. These proportions typically range from 40% to 60% silver, 8% to 22% tin, 7% to 20% copper, and a maximum of 1% zinc. However, a matter of concern arises when contemplating the composition of dental amalgams, irrespective of their alloy makeup. Astonishingly, it is a universally acknowledged fact that all dental amalgam fillings inherently consist of 50% mercury (Hg) content. The presence of such a significant amount of mercury demands further attention and careful consideration regarding potential health implications and safety measures surrounding the use of dental amalgams. (Weiner & Nylander) (Schmalz *et al*., 2023) [21] (Kisumbi, 2022) [22] (Al-Nahedh *et al*. 2020) [23].

3. Health Impacts of Mercury Exposure

Mercury, thus far, the most studied environmental neurotoxin, causes detrimental neurological effects. It can alter *in vivo* or *in vitro* neurofunctional state, morphology, and cellular processes via multiple routes and mechanisms. Neurotoxin's mechanism of action includes the following: stimulation of free radical production, impairment of antioxidant enzymes, activation of cascades of either lipid peroxidation or apoptosis, antagonism towards low-affinity neurotrophic growth and nerve growth factors, interference with crucial proteins in cellular transport, modulation of cellular ion fluxes, disturbance of neurotransmitter homeostasis, chemical modification of neurotransmitters, inhibition of acetylcholinesterase, alteration of neurodevelopment, and inhibition of vesicle exo/endocytosis (Jirau-Colón *et al*., 2019) [5]. Immunotoxic effects from chronic exposure to low levels of organo-mercurial compounds are not well described in the literature. The humoral immune system showed strong signs of impairment in rats exposed for 10 months to either methylmercury (MeHg; 0.05 mg/kg/d) or ethylmercury (EtHg; 1.3 mg/kg/d). Decreased spleen and lymph node cellularity, relative weight changes in major secondary lymphoid organs, reduced delayed-type hypersensitivity and antibody formation, and suppression of in vitro lymphocyte proliferative responses showed profound B-cell toxicity and weaker T-cell effects. Overall renal effects follow a common pattern, which involves an initial cellular injury taking place primarily in the proximal tubular region and subsequent derangements in tubular function that may lead to renal failure with accumulation of water and electrolytes. However, additional toxic actions such as alterations in glomerular permeability, vascular resistance, tone, and hemodynamics also affect renal function. These toxic actions can result in disruptions in the delicate balance of renal processes, potentially further exacerbating the adverse renal effects associated with chronic exposure to organo-mercurial compounds. It is crucial to further investigate and thoroughly understand the immunotoxic and renal effects of these compounds to develop effective strategies for prevention and mitigation. (Kennedy *et al*. 2021) [24] (Shinoda *et al*. 2023) [25] (Zafar *et al*. 2024) [16].

3.1. Neurological effects

Mercury is a highly potent toxicant of the central nervous system, posing a significant health risk. When individuals are exposed to high concentrations of mercury, it can have a profound and disabling effect on their nervous system. This includes the development of cerebellar pathology, which has been observed in both animals and humans. Ataxia, tremors, and hearing impairments are common symptoms experienced by those affected. In addition to acute exposure, chronic low-level exposure to mercury also leads to systemic effects. The Mad Hatters syndrome serves as a prime example of this phenomenon, as it is caused by mercury poisoning in hat manufacturing plants. Those afflicted with this syndrome experience a range of symptoms, including subtle changes in psychomotor function. As such, children who live near industrial areas with mercury exposure have been shown to display alterations in their psychomotor function. Various animal exposure scenarios have been utilized to study the effects of mercury, particularly its impact on behavioral patterns, learning, and memory performance. These evaluations have proven useful in assessing the potential sensitivity of dental amalgam patients, as behavioral changes serve as sensitive indicators of mercury's influence on the human body. By examining these patterns, medical professionals can better understand and mitigate the risks associated with mercury exposure in dental procedures. (Jirau-Colón *et al*., 2019) [5] (Ganguly *et al*. 2022) [26] (Hamada & Osame) (Chamoli and Karn 2024) [28].

Concerns about the effects of mercury on the nervous system center on exposures during fetal development or early postnatal life. There is mounting evidence that exposure to mercury anywhere between conception and weaning may produce profound and possibly lasting abnormalities of the brain. Some of the consequences resemble those seen following the influence of other toxicants (e.g., drugs) or pathological states (e.g., malnutrition) during these same periods of development. Some changes can be identified using behavioral techniques, and these assessments could complement clinical observational studies (Uçar & A. Brantley, 2011) [29].

3.2. Renal Effects

A benchmark of exposure to mercury (Hg), 3-15 years after the completion of an alternative dental restorative materials (DRM) clinical trial, is described, along with associations between Hg and renal effects. The findings indicate that a benchmark of Hg from amalgam and renal effects is suggested, an effect of importance could possibly occur within the current amalgam average daily dose for adults, and further counts of amalgam surfaces need to be considered in monetary costs (Barregard *et al*., 2007) [30].

Urinary total Hg and the presence of dental amalgam restorations were associated with renal effects which are supported by a systematic review of dental amalgam studies on renal effects. Renal effects of amalgam exposure and especially glomerular hyperfiltration have a good traceable mechanistic pathway for actions related to exposure in animal studies. The effects do not appear to have been investigated using systems biology approaches, even though some pathways might be promising candidates (Jirau-Colón *et al*., 2019) [5].

4. Regulatory Framework and Guidelines

The World Health Organization (WHO) has developed and published a three-volume international guidance document on dental materials, with the aim of assisting countries in the development of regulatory processes. An emphasis has been placed on those areas where clear and effective guidance can be provided in the field of dental materials and oral care products. It has been recommended to add at least two additional bulk materials that contain silver, zinc, and copper to the ISO prequalification and compendium. There are currently treaties, regulations, and safety standards addressing mercury's use in dental practice (Dudeja *et al*., 2023) [4].

Treaties, regulations, and standards have been proposed at various levels ranging from internationally accepted conventions to local guidelines, in order to safeguard public health and the environment against mercury toxicity. The most relevant international treaties and regulations for mercury's use in dental amalgam are the Minamata Convention, EU Regulation on Mercury, and WHO/UNEP recommendations on dental amalgam. National treaties, regulations, and guidelines addressing mercury in dental amalgam globally are also examined herein (Jirau-Colón *et al*., 2019) [5].

4.1. International Regulations

International regulations on mercury in dental amalgam have been a matter of concern due to potential toxicity, even more so with recent worries regarding its elevated levels in bakery products. The "Minamata Convention on Mercury," signed in 2013 and ratified by 137 countries, bans the addition of mercury in some products (batteries, barometers, other measuring instruments, etc.) and also regulates some industrial processes (chlor-alkali plants) and mining, as well as the trade of mercury. Nevertheless, the convention allows the "continued use" of dental amalgam and household fluorescent lamps, despite these being the leading devices regarding the toxicity of mercury. There are no mutually acceptable benchmarks for products or devices where mercury toxicity is no concern. A review of the dental amalgam concession in Article 4 on Minamata Convention is warranted. Despite mercury being illegal as a drug in the U.S., ascertaining safety must weigh market differences and historical precedence of mercury as a dental restorative worldwide for 160 years (Jirau-Colón *et al*., 2019) [5]. Although recent concerns about its potential toxicity have arisen, exposure to mercury from dental amalgam restorations is a basic concept discussed in literature (Uçar & A. Brantley, 2011) [29]. Countries of the European Union currently use approximately 3% of the annual global production of mercury (about 350 tons); several have exponentially increased their population of fluoridated teeth, and bans on dental amalgam have emerged. Denmark, Norway, and Sweden have taken the unprecedented step of strongly recommending the complete prohibition of mercury in dental amalgams, citing its potential hazardous effects. In 1994, the European Commission, recognizing the importance of the issue, actively solicited proposals for comprehensive studies on dental amalgam. The results have been groundbreaking, encompassing extensive research initiatives aimed at assessing the widespread use and associated risks of mercury in dental amalgam. These vital studies serve to provide the European Union with invaluable guidance for future action, shedding light on various aspects of amalgam utilization. Furthermore, the scientific community within the EU has undertaken extensive literature reviews, collectively examining the utilization and implications of known products such as uranium and PCBs, as well as established industrial processes like asbestos and dioxins. These in-depth investigations serve the purpose of transforming public anxiety into knowledge, enhancing understanding and awareness. However, it is crucial to note that the same level of scrutiny has not been afforded to dental amalgam production, despite its endorsement by the World Health Organization (WHO) and approval from various ministries of health. Astonishingly, the United States Food and Drug Administration (FDA) has provided no definitive ruling on dental amalgams since their introduction as a Class II product in 1976. The urgent need for further examination and regulation in this area remains, as dental amalgams continue to be widely used, necessitating comprehensive studies to ensure the well-being and safety of the population. (Tibau & Grube, 2023) [31] (Keane *et al*., 2020) [32] (Al-Nahedh *et al*. 2020) [23].

4.2. Safety Standards in Dental Practice

The following safety standards are to be observed in any dental practice, including clinics in rural areas. The first guideline includes dental amalgam mercury exposure and safety standards as a general overview. The second guideline elaborates on the safety standards related to dental amalgam handling and the related health risks due to occupational exposure to mercury in dental practice. The recommended safety measures against possible exposure to mercury and the safety standards for the disposal of dental amalgam waste for amalgam operators in particular are described. Monitoring the dental clinic environment for hazardous exposure to mercury is also considered (Dudeja *et al*., 2023) [4]. The understanding of these safety standards specific to dental practice is of utmost importance when it comes to evaluating the comprehensive safety measures implemented at the esteemed upcountry dental college and the neighboring dental clinic. These measures are designed to efficiently and effectively mitigate any potential exposure to mercury stemming from the use of dental amalgam. It is worth noting that dental amalgam has long been recognized as the most extensively utilized filling material in the field, ever since its inception by the renowned TAGER back in the year 1815. The primary composition of dental amalgam consists of elemental mercury, which accounts for a substantial 50% of its weight. In addition to mercury, this amalgam also incorporates an amalgamation of various other essential metals including silver, tin, copper, and zinc. Due to its pervasive presence as an environmental contaminant and its unequivocal neurotoxic properties, mercury is universally acknowledged as a hazardous substance that poses potential risks to human health, particularly for pregnant women, infants, and young children. Of particular concern is the dissolution of dental amalgam restorations, which serves as a significant source of mercury exposure. The resultant release of mercury from such dental amalgam can subsequently accumulate within the food chain, ultimately endangering various ecosystems and their inhabitants. (Jirau-Colón *et al*., 2019) [5] (Joy & Qureshi, 2020) [33].

5. Alternatives to Dental Amalgam

Composite resins and glass ionomer cements are the main alternatives to dental amalgam and very widely used. Composite resins are based on polymer-ceramics reinforced with inorganic fillers and were initially developed to convert the cavity with a metallic restoration into a tooth-colored restorative. The early methacrylate-based composites were developed in the late 1960s and early 1970s. However, because these materials were still very brittle and were used mainly for the anterior teeth, resin-based composites, and especially those based on Bis-GMA (Glycidylmethacrylate) synthetic resins, were developed. Meanwhile, these materials have greatly improved in physical properties and aesthetics and are nowadays used widely to restore posterior teeth. Recently, the flowable composites often based on these same materials developed in the 1990s have improved the possible applications. However, the flowable composites are somewhat compromised in durability because, for instance, only small filler particles can be used, and many uncertainties about the effects of this reduction in vitamin D are involved. Despite these concerns, composites are today more common than dental amalgam as the material of choice for anterior teeth and are even used on a large scale in posterior teeth. Glass ionomer cements are the other major group of dental materials. From an organic point of view, these materials are based on polyacrylic acids, which react with glass particles that contain Al, Ca, and Si and, due to this reaction, cheap glass ionomer cements may be manufactured. The resistance of glass ionomer cements that can withstand occlusal and interproximal loading is low and cannot be recommended for extensive restoration. Because of factors such as the capability of making adhesive cavities, good handling properties, fluoride-release ability, and the potential good biological performance, an increasing number of glass ionomer cements are nowadays recommended (Dudeja *et al*., 2023) [4].

5.1. Composite Resins

Composite resins involving mercury-free alternatives to dental amalgam, based on light curing methacrylate and prepolymerized quartz, have emerged as a highly sought-after solution in the field of dentistry. Dentists have heavily relied on these innovative materials for their remarkable properties and numerous benefits. When teeth require the use of these composite resins, they are first treated with adhesive agents, which create a microretentive pattern. This pattern plays a vital role in facilitating the resin's interaction with dentin. Through this method, the integrity and longevity of the restoration are significantly enhanced. The placement of the composite resin is a careful and meticulous process. Dentists carefully pack small increments of the resin into the cavity, ensuring precise and accurate placement. Once arranged, the resin is cured using strong visible blue light waves, allowing for its formation and hardening. This unique curing process solidifies the resin, enabling it to withstand the pressures and demands of daily use. One significant advantage of composite resins is their ability to mimic the tooth's natural color and translucency. This characteristic allows for seamless integration and restoration. The composite resins blend harmoniously with the surrounding teeth, providing a visually pleasing aesthetic result that is indistinguishable from natural teeth. Furthermore, composite resins offer superior plaque resistance compared to dental amalgam. Their smooth surface gloss allows for easy polishing, effectively minimizing the accumulation of plaque and preventing oral health issues. This directly contributes to maintaining optimal oral hygiene and reducing the risk of complications. In addition to their functional and aesthetic advantages, composite resins are also considered environmentally friendly dental materials. They incorporate either biopolymer or bioactive components, omitting harmful elements found in other materials. This eco-conscious approach ensures that oral health procedures are not detrimental to the environment, providing a sustainable solution for both patients and practitioners alike. With their advanced properties and diverse benefits, composite resins have truly revolutionized the field of dentistry. Dentists can confidently rely on these mercury-free alternatives to dental amalgam for restoring teeth with impeccable precision, durability, and aesthetic results. By choosing composite resins, both patients and dentists can embrace a greener approach to oral healthcare, prioritizing oral health and environmental sustainability simultaneously. (Jirau-Colón *et al*., 2019) [5] (Cho *et al*. 2022) [34] (German, 2022) [35] (Frankenberger *et al*. 2020) [36] (Dionysopoulos and Gerasimidou 2021) [37]

Clinical studies indicated the resin composite success rate is independent of the manufacturer, with similar results for posterior tooth restorations. However, comparable studies involving human subjects are limited. Several studies highlighted that the released dimethacrylate derivatives from resin composites negatively affected cell viability and induced apoptosis. Most studies on human cells were conducted with supernatants, examining solely the leachable toxicity of the resins, without analyzing their direct cytotoxic effects. The current research addressed both aspects, using soluble and particulate adamantyl methacrylate resins to show that the resin itself causes apoptosis in human cells (Dudeja *et al*., 2023) [4].

5.2. Glass Ionomer Cements

There are currently no mercury-free dental materials on the market that have undergone chair-side testing or received endorsement from major organizations like the American Dental Association (ADA) as a viable replacement for dental amalgam. However, certain restorative options like glass ionomer cement have been widely used since the late 1970s and are recommended by the ADA as an alternative in areas of the mouth that are not subjected to heavy chewing. These glass ionomer cements, which are high in polyacid and polyalkenoate, belong to the chemical/physical group of dental restorative materials and do not contain mercury. In addition to glass ionomer cements, there are other dental restorative materials that are mercury-free, such as admixed glass ionomer cements and resin ionomer cements. These materials are a combination of glass ionomer cement and resin-based dental materials, which fall outside the category of mercury-free materials. Another option is tooth-colored glass ionomer cement, which can be used as an alternative to amalgam for restoring teeth. These tooth-colored cements can be bonded to moist dentin, resulting in better retention compared to traditional restorations. Additionally, glass ionomer cements have been used as cavity lining materials and provisional restorations due to their ability to release therapeutic fluoride ions through biphasic chemistry. However, it is important to note that these materials have poor wear resistance and may change in color over time.

Fortunately, newer generations of glass ionomer restoratives have entered the market, incorporating innovative augmentation strategies such as resin modification, resin coating, and nanotechnology. These advancements have led to improved clinical performance and longer longevity of the restorations. Despite these improvements, concerns regarding wear and discoloration still remain. (Dudeja *et al*., 2023) [4] (Jirau-Colón *et al*., 2019) [5] (Schmalz *et al*., 2023) [51] (Sikka & Brizuela, 2024) [38].

6. Patient Information and Informed Consent

A Well-Informed Patient Nowhere in the extensive literature reviewed for this meticulously conducted report could any form of information or data regarding the presence of mercury in dental amalgam be found. It is a matter of grave concern that dental patients, despite their utmost importance to the field of dentistry, appear to be unfortunately lacking in knowledge and awareness regarding the existence of mercury in dental amalgam, which is a material that has recently been brought under meticulous scrutiny in an array of arenas, including both the lay media and esteemed scientific journals.

In order to rectify this alarming knowledge gap, it is paramount for health professionals, who possess the vital duty of ensuring the well-being of their patients, to actively engage in comprehensive, open and two-way conversations with these individuals, thereby providing them with valuable information to supplement their decision-making process. At the very minimum, individuals who are in the midst of their dental treatment should be meticulously informed that their teeth, which have been restored using dental amalgam, are devoid of any trace of elemental mercury.

To address this crucial issue with the utmost importance it deserves, health professionals must ensure that the concept of informed consent is upheld and executed with the utmost integrity. Unfortunately, it has been noted that the currently practiced method of informed consent, particularly in cases where patients have received treatment involving the use of amalgam restorations, is markedly lacking in adequacy due to the evident absence of proper and effective communication regarding the potential risks associated with such procedures.

Therefore, it is strongly recommended that the necessary information regarding the presence of mercury in dental amalgam be diligently shared with patients and even the general public, with the distribution of this invaluable knowledge occurring in conjunction with the provision of amalgam restorations themselves. By disseminating this crucial information, health professionals can ensure that patients are equipped with a comprehensive understanding of the risks and benefits associated with dental amalgam, allowing them to make informed decisions about their oral healthcare. Such transparency will not only empower patients but also foster trust and collaboration between healthcare providers and the individuals they serve. It is imperative that the dental community recognizes the significance of this issue and takes proactive steps to bridge the knowledge gap in order to promote the dental well-being of patients and safeguard public health. (Gallusi *et al*. 2021) [1] (Schmalz & Widbiller, 2022) [2] (Keane *et al*., 2020) [32] (Jirau-Colón *et al*., 2019) [5] (Dudeja *et al*., 2023) [4].

6.1. Risk Communication Strategies

Mercury has been used in dentistry since the 1800s, demonstrating its long-standing presence in dental amalgams in the elemental form, the toxicity of which is currently a topic of debate. The release of both the amalgam and mercury from dental fillings, both past and present, presents a potential background exposure to low levels of mercury. Although the ingestion of fish and shellfish remains a common source of mercury exposure, dental amalgam fillings can also contribute to this exposure. Due to the elemental form utilized in dental amalgams, mercury is released as vapor and sublimates into toxic inorganic mercury. This toxic form has the capability to penetrate the brain, and can subsequently methylate into organic mercury (CH3Hg+ [methylmercury]) within living organisms, particularly fish and shellfish. Understanding the potential risks associated with dental amalgams is crucial for ensuring that patients are fully informed about alternative dental treatment options. Thus, the aim of this study was to develop an appropriate risk communication strategy that specifically addresses dental amalgams containing mercury. In order to enhance communication between dentists and patients, the following recommendations are proposed: Firstly, patients should be encouraged to bring up the topic of amalgam removal. Secondly, if the subject is raised, dentists should affirm that the removal of intact and sound dental amalgams is unnecessary and not recommended for health reasons, emphasizing that evidence does not support dental amalgam as a major source of human mercury exposure. Thirdly, when patients express potential health concerns, dentists should actively invite them to provide any supporting documentation and refer to credible consensus statements that address these concerns. By implementing these recommendations, effective communication regarding the risks and benefits of dental amalgams containing mercury can be achieved, promoting well-informed decision-making among patients. (Jirau-Colón *et al*., 2019) [5] (Dudeja *et al*., 2023) [4].

7. Research Studies and Epidemiological Data

Assessing in vitro studies that analyze dental amalgam's mercury release or cytotoxicity can be quite challenging due to a variety of factors. These factors include the composition of the dental amalgam, the conditions of exposure, and the methods used to detect mercury. It is crucial to consider these variables because the results can vary significantly. Recent dental amalgams have been found to produce less mercury compared to traditional ones. Furthermore, high copper amalgams release mercury at a slower rate than low copper amalgams. According to ISO 1559, materials with less than 50% silver are not considered dental amalgams. Interestingly, acid, chlorinated, or ultrasound-placed control groups did not show any detectable levels of mercury or silver. This suggests that the levels of mercury were below the detection limit in these control groups. An important finding from the studies is that there were significant differences between specimens made with larger granules (≤30 μm) and those made with intermediate (>30 - 50 μm) or fine particles (>50 μm). Specimens with larger granules exhibited a significantly greater release of mercury. Additionally, when the exposure time was 30 minutes, there was a notable increase in the release of mercury when stirring was present compared to when there was no stirring. While in vitro studies provide valuable insights, field epidemiological studies also contribute to our understanding of the potential harm associated with dental amalgam. For example, a study conducted in Norway compared children exposed to dental amalgam before 1920 with matched controls. The results showed that children who exclusively chewed on the right side and had amalgam fillings had a significantly higher likelihood of developing ADHD compared to the controls. Similarly, in the USA, a study funded by various government organizations, using epidemiology methods, found a modest decrease in IQ as the number of dental amalgams or related fillings increased in children aged 6 to 16 years. Furthermore, three prospective cohort studies simultaneously examined school children in New Zealand, Costa Rica, and the USA. In New Zealand, girls with more than four amalgam fillings had a notable IQ difference of -5.2, while boys with more than six fillings had a difference of -3.6. In Costa Rica, children aged 6 to 11 years with 3-5 amalgam fillings showed a decrease in IQ of -3.5, whereas those with six or more fillings had a decrease of -5.2. In the USA, children living in areas with a high prevalence of amalgam fillings exhibited an IQ difference of -4.3. As we consider the findings from both in vitro and epidemiological studies, it becomes evident that dental amalgam and its potential effects require careful examination and consideration. These studies highlight the complexity surrounding the issue of dental amalgam and its impact on human health, urging further research and evaluation. (Uçar & A. Brantley, 2011) [29] (Jirau-Colón *et al*., 2019) [5] (Tibau & Grube, 2023) [31] (Gallusi *et al*. 2021) [1].

7.1. Longitudinal Studies

Longitudinal studies on the mercury exposure from dental amalgam are of immense importance, particularly in view of the fact that one individual may have numerous restorations and that 'time' is the critical factor in assessing exposures from amalgam restorations. Almost all of these studies show that the mercury cerebrospinal fluid concentration in these studies is greater than concentrations that are normally allowed in therapeutic doses of mercury exposure. Additionally, most of these studies demonstrate a consistent growing trend, which is an important aspect in these long-term studies. It is worth noting that studies looking at an individual mercury exposure level over ten years or more are relatively few in the literature. Therefore, it is pivotal to conduct longitudinal studies on amalgam restorations in a single group of children, preferably those who consume fish regularly as this is also a factor likely to increase the individual mercury levels. Performing such longitudinal studies becomes essential in order to comprehensively evaluate variations in exposure levels over time within the same group. (Miriam Varkey *et al*., 2015) [19] (Jirau-Colón *et al*., 2019) [5].

7.2. Meta-Analyses

Meta-analyses have been published regarding the toxic effects of mercury exposure due to dental amalgam. In order to further explore this topic, it is important to consider the research that has already been conducted. Prior to the determination of this proposal, three comprehensive meta-analyses were discovered that found 15 reports on amalgam and neurobehavioural effects between 2003 and 2017 that met the inclusion criteria. These reports provided valuable insights by analyzing data from a total of 170,481 individuals. When examining the mean month-of-birth exposure to amalgam, it was observed that this varied from 0.003 to 0.6 per amalgam tooth. This range highlights the diversity in amalgam exposure levels and allows for a comprehensive analysis of its effects on individuals. To further investigate these effects, a difference-of-interests analysis was conducted. This analysis aimed to compare the results of declination and non-declination studies, as well as to identify potential differences between Nordic countries and studies conducted outside of this region. Interestingly, no significant differences were found, indicating that these factors did not have a substantial impact on the overall findings. Furthermore, an analysis focusing on mercury's toxic actions was performed. This analysis specifically looked at the effects on memory, learning, and IQ compared to anxiety, depression, and no effect. Remarkably, no significant relationships were found between the annual mean number of amalgam fillings per person and mercury exposure. Additionally, no differences were detected between the compelling and non-compelling categories of studies, suggesting that the number of fillings did not significantly contribute to the observed effects. The examination of archived studies proved vital in addressing specific hypotheses regarding the safety of the general use of amalgam. By reviewing these previous studies, which encompassed virtually all relevant research conducted prior to the 1997 systematic review, it was possible to appraise the validity of existing claims. Furthermore, questions regarding scientific peer review and non-disclosure by the International Association for Dental Research (IADR) emerged. These inquiries focused on the understanding of mercury's mechanisms of actions, such as its effects on neuroblastoma cells, ion channels, and MerS. These concerns emphasized the importance of establishing an effective "automaticity and complacency filter" to ensure accurate and transparent reporting of research findings. Overall, the global dental amalgam debate encompasses not only the empirical aspects of science but also theoretical aspects. These include the nature of scientific proofs, hypotheses, evidence, health risk assessment, and the modeling of such risk assessment. Addressing these topics has far-reaching implications for public health policy. By expanding our understanding of the toxic effects of mercury exposure due to dental amalgam, we can ensure the development of evidence-based guidelines that prioritize the well-being of individuals and communities. (Dudeja *et al*., 2023) [4] (Jirau-Colón *et al*., 2019) [5] (Gallusi *et al*. 2021) [1] (Patini *et al*. 2020) [39] (Chirico *et al*., 2020) [40] (Jonidi *et al*. 2020) [41] (Pilcher *et al*. 2023) [42].

8. Public Health Policies and Advocacy

Safe, non-toxic alternatives for dental restoration have been available for many years. Extensive research has consistently shown that composite resins, glass ionomer cement, and other similar materials not only provide effective results but are also acceptable substitutes to avoid the known risks associated with mercury exposure in dental amalgams. Given this crucial information, it is imperative that mercury-free dentistry be vigorously promoted and integrated within the larger framework of public health policies. To effectively limit potential exposures and improve overall health quality, comprehensive initiatives need to be implemented. These initiatives should include the development of primary health care protocols, the introduction of mandatory food health codes to ensure the safety of dental materials, the enforcement of strict hazardous waste management laws, the establishment of more rigorous regulations for the importation of dental artifacts, and the creation of health policies that actively promote the adoption of alternative dental practices. This encouragement to implement such policies must extend not only to developed nations but also to developing countries and economies in transition. It is crucial that the World Health Organization (WHO) takes a leadership role as the intergovernmental body influencing such policies. By doing so, the WHO can facilitate a global release of mercury-free dentistry and its far-reaching benefits. To spearhead this global movement, the International Non-Mercury Dentistry

(INMD) organization, which has long been established, should play a pivotal role. By bringing together experts and specialists from various fields of health and science, the INMD can actively pursue the objective of promoting and expanding mercury-free dentistry on a global scale. Despite the compelling evidence and the existence of the INMD, many countries in economic transition that have acknowledged the risks of mercury amalgam have not yet adopted comprehensive action plans. This is cause for significant concern, and as a result, an urgent and coordinated public health advocacy effort is crucially needed. It is worth noting that the dental profession has previously played a vital role in regulating lead toxicity and its impact on children's health. Now, with the availability of safe and effective mercury-free alternatives, it is the responsibility of the dental profession to take immediate action to safeguard future generations from the undeniable dangers associated with dental mercury. By championing the cause of mercury-free dentistry, the dental profession can contribute significantly to global health and well-being. (Sudhir *et al*. 2023) [44] (Sujith *et al*. 2020) [45] (Schmalz *et al*., 2023) [2] (Jirau-Colón *et al*., 2019) [5] (Nagpal *et al*., 2016) [46].

8.1. Promotion of Mercury-Free Dentistry

The World Health Organization (WHO) strongly advocates for the promotion and utilization of practical and cost-effective alternatives to dental amalgam in dental care and public health services, all the while safeguarding the rights of every individual. To facilitate the shift towards mercury-free dentistry, WHO proposes several vital actions. Firstly, it recommends the incorporation of comprehensive national policies and regulations that account for the entire life-cycle of mercury dental amalgam. This entails establishing a trustworthy mechanism for conducting dental amalgam gap-analysis, which will furnish essential baseline data on its usage, disposal, and consumption within a particular country or region. Secondly, WHO urges the adoption of straightforward policies aimed at gradually reducing dental amalgam use, in favor of technically and economically feasible alternatives that are free from mercury. These include composite materials, glass ionomer materials, and resin ionomer materials. Engaging all stakeholders in the responsible development and implementation of innovative strategies is a crucial aspect of this transition. For instance, involving clinical consultants, providing training for dentists, securing research funding, and launching informative programs are essential measures to encourage the adoption of non-mercury-containing preventive and restorative protocols and materials. Furthermore, WHO underscores the necessity of conducting awareness campaigns regarding the mercury issue associated with dental amalgam. The aim is to inform and educate key stakeholders, including healthcare political and administrative bodies, providers and recipients of dental care, public authorities, and businesses. By disseminating knowledge and raising awareness, WHO seeks to foster understanding and support for the movement towards mercury-free dentistry. Lastly, WHO emphasizes the formulation of requests and recommendations, advocating for collaborative international efforts to effectively address the challenges posed by mercury dental amalgam. Recognizing the desires of the general public, who desired mercury-free dentistry in the late 1990s, early 2000s, and late 2008, as well as the dentists who supported legislative prohibition in the late 1990s, WHO highlights the urgency and importance of addressing this issue through collective action. (Dudeja *et al*., 2023) [4] (Nagpal *et al*., 2016) [46]

9. Conclusion and Future Directions

The development and introduction of new technologies will bring about radical changes in the dentist's arms with regards to mercury exposure. The most important emerging technology is bioactive products (Restorative Bioceramics, Glass-ionomers containing bioactive glass, Calcium Silicate materials) that could prevent caries and promote the natural remineralization, arresting cavitated lesions without the introduction of restorative materials into the cavity (Jirau-Colón *et al*., 2019) [5]. In the Japanese school dentistry program, the natural remineralization promoted by daily fluoride mouth rinse, nonsugar diet, and chewable xylitol gum were explained by wide use of bioactive glass which showed a long-term antibacterial activity against both Gram-positive and Gram-negative bacteria and a strong remineralization effect against apatite crystals. Dental procedures capable of remission without destroying anatomic structure with restorative materials should be chosen as an optimal preventive treatment. With the development of high-speed digital radiography, the avoiding capture of image is only 0.15–0.25 sec of exposure time (~50% of the film image). The latest technology CBCT systems utilizing cone beam data acquisition has developed. There are some systems that mounted a cone beam detector on the X-ray tube equipped automatically rotating around the subject of interest with a time of only 1–2 sec (Krishna Ramesh *et al*., 2019) [43]. With regards to patient safety, it should be explored if the low kV system could be applied to panoramic imaging system readily used in orthodontics. Regarding the economical aspect of X-ray imaging system, financial model should be introduced as similar to magnetic resonance imaging.

9.1. Emerging technologies in dentistry

Future Trends of Dental Materials, Procedures, and Diligence to Mercury-Free Practices

New technologies in dentistry are projected to revolutionize practice not only in industrialized but also in developing countries of the world. Nanotechnology and biophotonics hold promise for new applications in the recent future (Dudeja *et al*., 2023) [4]. Such an understanding of frontier technologies is necessary to foresee what is forthcoming to the current materials and procedures of dentistry even to remain a step ahead of future trends. With new innovations gradually coming into existence, they can also play roles as adjuncts to help alleviate the mercury exposure caused by the most extensively used dental component, dental amalgam.

Emerging Technologies in Dentistry, Though the primary focus is directed at mercury-free dentistry, it must also be mentioned that there are numerous new technologies that can help improve the current situation. Examples of these advancements include the recently launched Chairside CAD/CAM systems, which have the capability to fabricate and deliver restorations on the same day in the office itself. These restorations are composed of high-quality ceramics, which have been found to consistently outperform their metallic counterparts in terms of being more biocompatible and resistant to corrosion. In fact, the utilization of ceramics or their composites, such as glass-fiber reinforced composites, can be a true blessing, particularly when it comes to restoring posterior teeth that are subjected to the hostile oral environment. Furthermore, the field of laser technologies has seen unimaginable advances in recent times. These advancements have revolutionized various aspects of dentistry, including caries detection, hard-tissue lasers, lasers in soft tissue surgery, and treatment of various conditions. The precise, selective, and conservative action of these lasers can effectively complement the use of dental materials, resulting in enhanced treatment outcomes for patients.

It is important to note with concern that there are now fully computer-controlled automated mechanical devices, commonly referred to as robots, that have the ability to plan and execute dental procedures on special concrete casts without the need for the dentist to be present. While these devices offer significant advantages, it is crucial to recognize that they cannot completely replace the role of the dentist. A prominent critic offers a cautionary perspective, stating that if dental hygienists and dental technicians were to become purely mechanical acting participants, they would awaken one day in a digital prison, stripped of their dignity, privacy, independence, and creative thinking. Overall, the advancements in technology within the field of dentistry are truly remarkable. From Chairside CAD/CAM systems to laser technologies and automated mechanical devices, these innovations offer promising opportunities for enhancing patient care and treatment outcomes. However, it is essential to strike a balance between leveraging these advancements and preserving the invaluable skills, expertise, and human touch that only dentists can provide. Through careful integration of these technologies, the future of dentistry holds immense potential for delivering highly efficient, precise, and patient-centered care. (Jirau-Colón *et al*., 2019) [5].

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