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Thyroid Response to Mercury: Varied Effects on Function and Structure - A Review of the Latest Research

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ABSTRACT

Introduction

In the current era of burgeoning industry, our exposure to various detrimental environmental factors, including mercury, has become increasingly prevalent. Recognized by the World Health Organization (WHO) as one of the most significant threats to public health, mercury induces a multitude of harmful effects on the entire body. Our focus in this article will be directed towards examining the specific impact of mercury on the thyroid.

Purpose of the study

The purpose of the study was to review the latest literature on the effects of mercury on the thyroid gland.

Materials and Methodology

Literature selections of medical databases PubMed and Google Scholar from the last six years (2017-2023) were performed. Articles were searched in English using the following key words: mercury, thyroid.

Results

Research consistently confirms mercury accumulation in thyroid cells, increasing with age. Mercury exposure influences thyroid function, raising the risk of hormonal issues and potential thyroid cancer. It also interacts with other elements, compounding adverse effects on the thyroid.

Conclusion

Presently, there is a limited number of studies specifically addressing the effects of mercury on the human thyroid gland. Consequently, it is probable that the full spectrum of its impacts on the thyroid has not yet been thoroughly investigated. Further research is imperative to delve into this subject comprehensively. Additionally, there is an urgent call for initiatives aimed at enhancing public awareness regarding the sources of mercury in the environment and food, along with strategies to mitigate exposure to this harmful substance.

Keywords: mercury, thyroid

I. Introduction

Mercury (Hg) is a heavy metal that exists in various forms (organic, inorganic, and elemental) within the environment, present in air, water, soil, and living organisms [1,2]. The human body can be exposed to mercury through ingestion, inhalation, and skin absorption [3]. Given its non-biodegradable nature as a heavy metal, the amount of mercury tends to increase as it ascends the food chain. The primary source of mercury in the human body is through the consumption of fish containing methylmercury, an organic form of mercury known for its significant toxicity to humans. This methylmercury originates from atmospheric mercury vapor [4]. The emission of mercury into the atmosphere is predominantly attributed to widespread human activities, including the burning of fossil fuels, emissions from coal-fired power plants, heating systems, and the mining industry [5].

Mercury, recognized by the World Health Organization (WHO) as one of the substances of utmost public health concern, possesses the capability to accumulate in diverse tissues and organs within the human body. Even in trace amounts, it has the potential to induce severe health issues, encompassing neurotoxicity, respiratory and cardiovascular toxicity, digestive and immune system complications, reproductive system toxicity, and adverse effects on the kidneys, skin, eyes, and thyroid gland [4,5]. Moreover, mercury in all its forms can be detected in hair, nails, kidneys, and the liver. It is excreted through saliva, sweat, tears, and breast milk [6]. This characteristic makes mercury capable of spreading within the environment and among organisms. In our article, we have chosen to specifically delve into the effects of mercury on the thyroid gland.

II. Purpose of the study

The purpose of the study was to review the latest literature on the effects of mercury on the thyroid gland.

III. Materials and Methodology

Literature selections of medical databases PubMed and Google Scholar from the last six years (2017-2023) were performed. Articles were searched in English using the following key words: mercury, thyroid.

IV. Description of the state of knowledge

IVa. Mercury in the thyroid gland according to age

In a 2021 study, Roger Pamphlett and colleagues investigated the prevalence and distribution of mercury in the thyroid gland across different age groups. Utilizing autometallography, followed by laser ablation and inductively coupled plasma mass spectrometry, the researchers analyzed thyroid samples from 115 individuals (68 men and 47 women) aged 1-104 years, encompassing various clinical pathological conditions. Mercury was identified in thyroid follicular cells in 22 out of the 115 samples. Stratifying these findings by age groups revealed mercury presence in the thyroid gland in 4% of those aged 1-29, 9% of those aged 30-59, and 38% of those aged 60-104 ($p < 0.0001$). In summary, the study demonstrated that the frequency of mercury occurrence in the thyroid gland, specifically within follicular cells, increases with age [7].

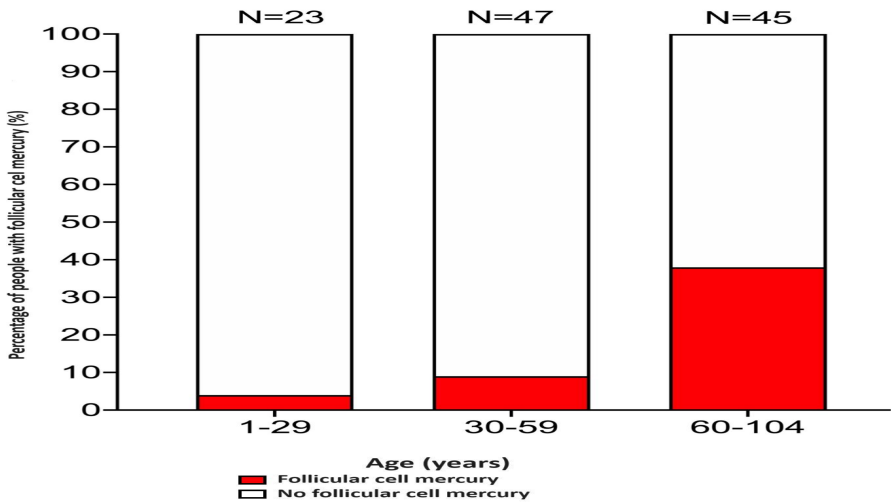

Figure 1. Proportion of individuals with mercury detected in thyroid follicular cells: 4% in the age group of 1-29 years old, 9% in the age group of 30-59, and 38% in the age group of 60-104. The numbers above the bars represent the respective counts in each age group [7].

In another study conducted by Roger Pamphlett, examining the presence of inorganic mercury in various tissues and organs of individuals aged 1-104 years, similar conclusions were drawn. The research revealed that mercury is not only commonly found in thyroid cells but also in the brain, kidneys, adrenal medulla, pituitary gland, and other organs. Additionally, mercury tends to be present simultaneously in multiple organs within an individual.

The study indicated an increase in the prevalence of people with inorganic mercury in organs with age, reaching a peak between 61 and 80 years. However, a decline in the prevalence of mercury in multiple organs was observed after the age of 80. In the case of the thyroid gland, the decrease in prevalence among individuals over 80 with mercury in this organ from its peak was only 8%, possibly linked to the stabilization of mortality in this age group [8]
The hypothesis suggests that very elderly individuals, in general, have lower mercury levels in their tissues, potentially contributing to their longevity and avoiding premature death [9,10].

IVb. Mercury and thyroid pathologies

The effects of mercury poisoning on thyroid and other organ function based on cases of pediatric patients were recently described by researchers Yavuz Özer and colleagues. Patients were diagnosed most often with hypertension, tachycardia, pain and irritability in the extremities, and uncharacteristic rashes. In 5 of the 6 cases of mercury poisoning, there were elevated levels of thyroid hormones (fT3 and/or fT4) with normal thyrotropin (TSH) levels.
Mean blood mercury level was 31.01 ± 28.31 ug/L and the mean mercury level in 24-hour urine was 1301.25 ± 963.57 ug/g creatinine. The mean fT3, fT4, TSH and values were found to be 4.78 ± 0.72 pg/mL, 2.07 ± 0.4 ng/dL, and 1.67 ± 0.88 uIU/mL, respectively [1]. Normal unsuppressed TSH levels, may be due to the accumulation of mercury in the thyroid and pituitary gland, and disruption of the hypothalamic-pituitary-thyroid axis [11].
In addition, it has been shown that the effects of mercury on the thyroid gland can vary depending on the route and time of exposure, as well as the dose, affecting the occurrence of individual symptoms and their severity. Treatment of mercury poisoning has included dimercaptosuccinic acid (DMSA), metamizole, antihypertensive drugs, and anticonvulsants, antipsychotics and other drugs when indicated. The period of remission of thyroid dysfunction after the introduction of treatment ranged from 2 to 24 weeks (average 9.7 ± 7.4 weeks) in the cases described. However, the long-term effects of acute mercury poisoning on thyroid function have not been studied [1].
In 2020, Hu Q et al. performed a meta-analysis to determine the relationship between mercury exposure and thyroid hormone levels in the general population. To assess thyroid function, levels of the following hormones were considered: thyrotropin (TSH), triiodothyronine (T3), thyroxine (T4), free triiodothyronine (FT3) and free thyroxine (FT4). The meta-analysis indicates that mercury exposure may significantly correlate with TSH, T4 and FT4 levels in the general population, as whenever mercury was detected in the blood, an increase in TSH, T4 and FT4 levels was observed in study participants, while no statistically significant

association was found between the presence of mercury in the blood and T3 and fT3 levels. In addition, there was no association between urinary mercury levels and TSH [12].

A Korean research institute led by Min Joo Kim conducted a study between 2015 and 2017 to investigate the effects of heavy metals and polycyclic aromatic hydrocarbons (PAHs) in the environment on the human body, including thyroid hormone levels and thyroid parenchyma. The levels of mercury (Hg), lead (Pb), cadmium (Cd) and four PAH metabolites in urine or total blood were examined. In addition, thyroid hormones (T3 and T4), TSH, thyroxine-binding globulin (TBG) and thyroid autoantibodies were determined, and peripheral deiodinase (GD) activity and thyroid secretory capacity (GT) were calculated. Blood mercury in men was positively related to free T4, while in women blood Hg was positively related to total T3 levels. Urinary Hg was negatively correlated with total T3 in both men and women, and positively correlated with total T4 levels, but only in women. In addition, urinary Hg was associated with decreased deiodinase activity and increased thyroid secretory capacity in both sexes. The findings present in the study suggest that mercury exposure may disrupt thyroid hormones, and most likely by altering deiodinase activity [13].

A similar topic was addressed by Hai Duc Nguyen in his study focused on the effects of mixed chemicals (including mercury) on the levels of four important hormones: T3, T4, TSH, FSH. The researcher used data from the Korean National Environmental Health Survey (KoNEHS) from 2012 to 2014, and included 5867 adults in whom the presence of thyroid disease had been ruled out. Based on urine and blood samples taken from the participants, the levels of said hormones and harmful chemicals including mercury were determined. Among other things, it was observed that mercury levels in the blood were positively related to T3 concentrations. In addition, it was discovered that mercury affects 16 genes associated with thyroid disease. Even 5 key genes (CAT, PTGS2, IL1B, IL6, and TNF) responsible for mercury-induced thyroid disease have been demonstrated. Using analysis of protein-protein interaction enrichment (PPIE) data, Hai Duc Nguyen demonstrated three major molecular mechanisms through which mercury affects the thyroid, namely the selenium micronutrient network, the IL-17 signaling pathway, and the oxidative stress response. It is also proven that poorly differentiated thyroid cancer and primary hyperthyroidism are the main mercury-induced diseases of this organ [14].

In 2016-2017, a cross-sectional study was conducted by Correia et al. to assess the effects of chronic occupational exposure to metallic mercury on the thyroid gland. The study included 110 men-half of whom had a history of chronic mercury exposure, the other half not. In the participants, both the parenchyma of the thyroid gland using B-mode Doppler ultrasound and

the endocrine function of this organ were assessed by measuring the concentration of individual parameters in the blood: total and free triiodothyronine (TT3, FT3), free thyroxine (FT4), thyrotropin (TSH), reverse T3 (RT3), selenium and antithyroid antibody. Nodules detected on ultrasound with features indicative of potential malignancy were subjected to fine-needle aspiration biopsy. In addition, urinary mercury and iodine concentrations were measured. Taking into account these findings, the two groups were compared using statistical tests. As a result, it was summarized that in the mercury-exposed group, the mean blood TSH concentration was statistically significantly higher than in the unexposed group. The number of echogenic changes detected by Doppler ultrasound in the mercury-exposed group was also higher. In addition, 3 papillary thyroid carcinomas were diagnosed in the exposed group, while 1 papillary and 1 follicular carcinoma were diagnosed in the unexposed group. However, there was no statistical difference in the levels of TT3, FT3, FT4 between the two groups. The study concluded that chronic mercury exposure affects the parenchyma and function of the thyroid gland even after cessation of chronic exposure [15].

In 2020, a paper was published by V. Maggisano et al. on exposure to environmental endocrine disruptors. The study also considered the effect of mercury on the increased risk of thyroid pathology frequency. The results presented in the study show the toxicity of even non-weil concentrations of methylmercury (MeHg) on thyroid parenchymal cells. It has been shown that chronic mercury exposure can affect thyroid cell proliferation by affecting the prooncogenic signal transduction pathway via the ERK pathway [16].

A similar topic was addressed in a study conducted between 2003 and 2011 on a population of residents in industrial areas of South Korea. It focused on the relationship between mercury exposure and thyroid cancer risk. 5213 participants were analyzed, and 69 cases of thyroid cancer were registered during a median follow-up of 8.7 years.

The results showed a positive correlation between urinary mercury concentration and thyroid cancer risk. Participants with the highest tercile of mercury concentrations had twice the risk of thyroid cancer compared to those with the lowest tercile. Importantly, the observed association between mercury exposure and thyroid cancer was more pronounced in those with lower MCV and MCHC [17].

Also, another recent study found that mercury, like other heavy metals (cadmium, arsenic), contributes to a number of cancers including: thyroid, skin, liver, prostate, lung, bladder, kidney and gastrointestinal. The study also sheds light on the role of microRNAs (miRNAs or miRs) in the context of induction of carcinogenesis by heavy metals [6].

Another adverse effect of mercury on the thyroid gland was revealed by a clinical trial being conducted in 2019. The aim of the study was to determine heavy metal and phthalic ester levels in adolescents with thyroid colloid cysts. Participants in the study were 12- to 15-year-olds with a diagnosis of thyroid colloid cyst- TCC (study group 1) and gender- and age-matched subjects without such a diagnosis (control group 2). Heavy metal levels were tested using urine samples. The study found that adolescents with higher mercury level scores had an increased risk of TCC [18].

The meta-analysis by Benvenga et al. (2022) took into account the effects of mercury in fish and seafood on the thyroid gland and the autoimmunity that can take place just inside this organ. One study evaluated the association between total mercury levels in the blood and positive thyroid antibodies (thyroglobulin-TgAb and thyroperoxidase-TPOAb antibodies). Twenty-four hundred and forty-seven women were examined, proving a positive association between mercury levels and a higher TgAb score. However, there was no significant association with a positive TPOAb score [4].

A 2018 study by Rezaei et al. to assess trace metal levels-including mercury-in healthy individuals (group 1) and those with thyroid diseases-hyper/hypothyroidism, thyroid cancer (group 2) yielded different results. The study included 110 participants, in whom thyroid hormone levels were measured, as well as levels of the elements checked in the blood. Statistical tests made it possible to assess the difference between the groups. Based on the study's findings, the authors concluded that toxic metals like Cr, Cd, and Pb may elevate the risk of hypothyroidism and thyroid cancer. Interestingly, Hg showed no correlation with other elements in the development of hypothyroidism but demonstrated a potential influence on hyperthyroidism, particularly when combined with cadmium[19].

In contrast, a study by Maths Berlin and colleagues on the effects of mercury present in dental amalgam on the human body showed subclinical effects of Hg on thyroid function at exposure levels equal to the upper end of the exposure range observed in amalgam carriers. In addition, it was speculated that mercury's toxic effects on cells are based on its ability to modify the tertiary and quaternary structure of proteins. Since protein structure is genetically determined, genetic polymorphisms may manifest themselves in different sensitivity and response to mercury exposure, including in the thyroid [20].

IVc. Effects of mercury on thyroid in pregnant women and fetuses

A prospective, cohort study conducted by Wang et al. (2020) was designed to determine the important window of pregnant women's exposure to metals for maternal and neonatal thyroid

function - the effects of mercury were also considered. In pregnant women, urinary levels of individual metals were assessed in the 1st and 3rd trimesters of pregnancy, and thyroid hormone levels (TSH, FT4) were examined in the 2nd and 3rd trimesters using electrochemiluminescent microparticle immunoassays. To study thyroid function in newborns, TSH levels were determined on day 3 after birth from a heel prick blood sample. The results of the study presented above show that pregnant women's exposure to mercury in the 1st trimester of pregnancy is positively correlated with her TSH level in the 2nd trimester. Mercury concentration (as opposed to Cd and Cs) in the 1st trimester in the mother's urine, on the other hand, was not related to TSH levels in the newborn. It has been established that the 1st trimester is a critical time when heavy metals have long-term effects on thyroid function in the mother and the newborn [21].

Between March 2009 and July 2012, a cohort study was conducted to examine the association between perfluoroalkyl acids (PFAAs) and thyroid function in pregnant and postpartum women, including thyroid peroxidase antibodies (TPOAb) and mercury (Hg) exposure. The study included 2,140 women from the metropolitan areas of Edmonton and Calgary, Alberta, Canada. The analysis found that certain PFAAs, particularly perfluorohexane sulfonate (PFHxS) and perfluorooctane sulfonate branched isomers (PFOS), were associated with abnormalities in thyroid function, such as elevated thyrotropic hormone (TSH) levels and reduced free thyroxine (FT4) levels. In addition, mercury (Hg) exposure was shown to affect these compounds, compounding the negative effects of PFAAs on thyroid function. The results suggest that PFHxS and PFOS branched isomers may be risk factors for subclinical hypothyroidism in pregnant women, especially in those with TPOAb [22].

V. Conclusion

In summary, findings from various studies indicate a connection between mercury exposure and thyroid dysfunction. Mercury has been unequivocally demonstrated to accumulate in thyroid cells, with the prevalence of Hg in the thyroid gland increasing with age. Meta-analyses reveal a notable correlation between mercury exposure and thyroid hormone levels, particularly TSH, T4, and FT4. Experimental studies on thyroid cells suggest that mercury may influence cell proliferation and interact with pro-oncogenic pathways. Additional research on the impact of heavy metals, including mercury, on thyroid function supports the possibility of endocrine disruption. A Korean study identified an association between mercury in urine, decreased deiodinase activity, and increased thyroid secretory capacity. Studies from China and the US also highlight connections between exposure to a mixture of heavy metals

and thyroid hormone levels. Epidemiological studies involving populations with occupational mercury exposure indicate subclinical effects on thyroid function, particularly at elevated exposure levels. Notably, there is growing interest in investigating the potential link between mercury exposure and the development of thyroid cancer. Research from South Korea, along with a comprehensive literature review, suggests a potential heightened risk of thyroid cancer associated with exposure to mercury.

The overarching findings from these studies suggest that mercury exposure may affect thyroid function, increasing the risk of hormonal abnormalities and potentially the risk of developing thyroid cancer. However, due to the complexity of interactions between different chemicals and individual differences in the body's response, further research is needed to better understand these relationships and identify effective preventive measures. Additionally, efforts should be directed towards enhancing public awareness regarding the detrimental effects of mercury on the human body, understanding sources of mercury in the environment and food, and adopting strategies to minimize exposure to this harmful substance.

DISCLOSURE

Author's contribution:

Conceptualization: Nina Taborska, Anna Martyka, Martyna Kubicka-Figiel

Methodology: Nina Taborska, Anna Martyka, Martyna Kubicka-Figiel

Software: Nina Taborska, Anna Martyka, Martyna Kubicka-Figiel

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Project Administration: Nina Taborska, Anna Martyka, Martyna Kubicka-Figiel

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List of figures:

Figure 1. Proportion of individuals with mercury detected in thyroid follicular cells [7].

References:

1. Özer Y, Yıldız M , Turan H, et al. Temporary Thyroid Dysfunction and Catecholamine Excess Due to Mercury Poisoning in 6 Cases. Turk Arch Pediatr. 2023 Oct 11. https://doi.org/10.5152/TurkArchPediatr.2023.23150. PMID: 37818842
2. Zeng X, Huo X, Xu X, et al. E-waste lead exposure and children's health in China. Sci. Total Environ. 2020 Sep10:734:139286. DOI: 10.1016/j.scitotenv.2020.139286. PMID: 32460072

3. Liu D, Shi Q, Liu C et al. Effects of Endocrine-Disrupting Heavy Metals on Human Health. Toxics. 2023 Mar 29;11(4):322. https://doi.org/10.3390/toxics11040322. PMID: 37112549
4. Benvenga S, Famà F, Perdichizzi LG, et al. Fish and the Thyroid: A Janus Bifrons Relationship Caused by Pollutants and the Omega-3 Polyunsaturated Fatty Acids Front Endocrinol (Lausanne). 2022 May 27:13:891233. https://doi.org/10.3389/fendo.2022.891233. eCollection 2022. PMID: 35712237
5. https://www.who.int/news-room/questions-and-answers/item/mercury-health (the date the file was displayed: 6.01.2023).
6. Aalami AH, Hoseinzadeh M, Manesh PH et al. Carcinogenic effects of heavy metals by inducing dysregulation of microRNAs: A review. Mol Biol Rep. 2022 Dec;49:12227–12238. DOI: 10.1007/s11033-022-07897-x PMID: 36269534
7. Pamphlett R, Doble PA, Bishop DP. Mercury in the Human Thyroid Gland: Potential Implications for Thyroid Cancer, Autoimmune Thyroiditis, and Hypothyroidism. PLoS One. 2021 Feb 9;16(2):e0246748. https://doi.org/10.1371/journal.pone.0246748. eCollection 2021. PMID: 33561145.
8. Pamphlett R. The prevalence of inorganic mercury in human cells increases during aging but decreases in the very old. Sci Rep. 2021 Aug 18;11(1):16714. doi: 10.1038/s41598-021-96359-8. PMID: 34408264; PMCID: PMC8373952
9. Barbi E, Lagona F, Marsili M, et al. The plateau of human mortality: Demography of longevity pioneers. Science Jun 29;360(6396):1459-1461. DOI: 10.1126/science.aat3119. PMID: 29954979
10. Gampe, J. (2021). Mortality of Supercentenarians: Estimates from the Updated IDL. In: Maier, H., Jeune, B., Vaupel, J.W. (eds) Exceptional Lifespans. Demographic Research Monographs. Springer, Cham. https://doi.org/10.1007/978-3-030-49970-9_3
11. Khan R, Ali S, Mumtaz S, et al. Toxicological effects of toxic metals (cadmium and mercury) on blood and the thyroid gland and pharmacological intervention by vitamin C in rabbits. Environ Sci Pollut Res Int. 2019;26(16):16727-16741.
12. Hu Q, Han X, Dong G, et al. Association between mercury exposure and thyroid hormones levels: A meta-analysis. Environ Res. 2021 May:196:110928. Epub 2021 Feb 26. https://doi.org/10.1016/j.envres.2021.110928. PMID: 33640496.
13. K Joo Min, K Sunmi, Ch Sohyeon et al. Association of exposure to polycyclic aromatic hydrocarbons and heavy metals with thyroid hormones in general adult

population and potential mechanisms. Sci Total Environ. 2021 Mar 25:762:144227. Epub 2020 Dec 13. https://doi.org/10.1016/j.scitotenv.2020.144227. PMID: 33373756.

14. Nguyen HD. Exposure to mixed chemicals elevated triiodothyronine (T3) and follicle-stimulating hormone (FSH) levels: epidemiology and in silico toxicogenomic involvement. Environ Sci and Pollut Res Int. 2023 Aug;30(38):88803-88823. DOI: 10.1007/s11356-023-28704-5. PMID: 37442928.
15. Correia MM, Chammas MM, Zavariz JD, et al. Evaluation of the effects of chronic occupational exposure to metallic mercury on the thyroid parenchyma and hormonal function. Int Arch Occup Environ Health 2020 May;93(4):491-502. https://doi.org/10.1007/s00420-019-01499-0. Epub 2019 Dec 12. PMID: 31832764.
16. Maggisano V, Bulotta S, Celano M, et al. Low Doses of Methylmercury Induce the Proliferation of Thyroid Cells In Vitro Through Modulation of ERK Pathway. Int J Mol Sci. 2020 Feb:25;21(5):1556 https://doi.org/10.3390/ijms21051556. PMID:32106432.
17. Kim S, Song SH, Lee CW et al. Low-Level Environmental Mercury Exposure and Thyroid Cancer Risk Among Residents Living Near National Industrial Complexes in South Korea: A Population-Based Cohort Study. Thyroid. 2022 Sep;32(9):1118-1128. DOI: 10.1089/thy.2022.0084. PMID: 35950626.
18. Songül Yalçin S, Erdal İ, Çetinkaya S, et al. Urinary levels of phthalate esters and heavy metals in adolescents with thyroid colloid cysts. Int J Environ Health Res. 2022 Jun;32(6):1359-1372. https://doi.org/10.1080/09603123.2021.1883554. Epub 2021 Feb 8. PMID: 33555204.
19. Rezaei M, Javadmoosavi SY, Mansouri B, et al. Thyroid dysfunction: how concentration of toxic and essential elements contribute to risk of hypothyroidism, hyperthyroidism and thyroid cancer. Environ Sci Pollut Res Int. 2019 Dec;26(35):35787-35796. https://doi.org/10.1007/s11356-019-06632-7. Epub 2019 Nov 8. PMID: 31701424.
20. Berlin M. Mercury in dental amalgam: a risk analysis. Neurotoxicology. 2020 Dec:81:382-386. Epub 2020 Oct 14. https://doi.org/10.1016/j.neuro.2020.09.034. PMID: 35623360.
21. Wang X, Sun X, Zhang Y, et al. Identifying a critical window of maternal metal exposure for maternal and neonatal thyroid function in China: A cohort study. Environ

Int. 2020 Jun:139:105696. https://doi.org/10.1016/j.envint.2020.105696. Epub 2020 Apr 4. PMID: 32259758.

22. Reardon AJ, Moez EK, Dinu I, et al. Longitudinal Analysis Reveals Early-Pregnancy Associations between Perfluoroalkyl Sulfonates and Thyroid Hormone Status in a Canadian Prospective Birth Cohort. Environ Int. 2019 Aug:129:389-39 9. https://doi.org/10.1016/j.envint.2019.04.023. Epub 2019 May 28. PMID: 31150980