Original Research

HEAVY METAL TOXICITY AND CHRONIC KIDNEY DISEASE IN SOUTHERN TAMIL NADU: CHALLENGES, MECHANISMS, AND PUBLIC HEALTH PERSPECTIVES

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ABSTRACT
Chronic Kidney Disease (CKD) represents a significant global health burden, characterized by a progressive decline in renal function. While traditional risk factors such as diabetes and hypertension are well-established, the role of environmental pollutants, particularly heavy metals, in the etiology and progression of CKD is gaining increasing attention. This comprehensive review synthesizes current knowledge on the impact of heavy metal exposure on CKD, with a specific focus on findings from the Southern Tamil Nadu population. It delves into the mechanisms by which various heavy metals, including but not limited to arsenic, lead, cadmium, and mercury, exert nephrotoxic effects, leading to cellular damage, glomerulosclerosis, and impaired renal function. The review also examines the prevalence of heavy metal exposure in susceptible populations, routes of exposure, and the challenges in establishing clear causal links due to the heterogeneity of environmental factors and population demographics. Furthermore, it discusses diagnostic approaches, potential therapeutic interventions, and the critical need for effective management strategies to mitigate the adverse health outcomes associated with heavy metal-induced nephropathy. By integrating findings from recent studies and highlighting the unique context of Southern Tamil Nadu, this review aims to provide a deeper understanding of this complex public health issue and underscore the importance of environmental monitoring and public health interventions to prevent and manage CKD.

Keywords:

INTRODUCTION
Chronic Kidney Disease (CKD) is a progressive and irreversible condition defined by abnormalities of kidney structure or function, present for more than three months, with implications for health [1-3]. Globally, CKD affects an estimated 10-15% of the adult population, contributing significantly to morbidity, mortality, and healthcare costs [4, 5]. The rising prevalence of CKD is attributed to an aging population and an increase in risk factors such as diabetes mellitus (DM), hypertension (HTN), obesity, and cardiovascular diseases [6, 7]. While these conventional risk factors are extensively studied, a growing body of evidence points towards the significant, yet often overlooked, contribution of environmental factors, particularly exposure to heavy metals, in the development and progression of CKD [8].

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Heavy metals are naturally occurring elements with high atomic weights and densities, typically five times greater than water [9]. While some, like zinc, copper, and selenium, are essential micronutrients at low concentrations, others, such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), are highly toxic even at trace levels and have no known physiological role in the human body [10-12].

Human exposure to these metals occurs through various pathways, including contaminated food and water, occupational exposure, air pollution, and certain traditional medicines [13]. Once absorbed, heavy metals can accumulate in various organs, with the kidney being a primary target due to its role in filtering and excreting toxins from the bloodstream [14]. The kidney's high metabolic activity and rich blood supply make it particularly vulnerable to heavy metal-induced damage, leading to a spectrum of renal pathologies ranging from acute kidney injury to chronic tubulointerstitial nephritis and glomerulosclerosis [15-17]

In regions like Southern Tamil Nadu, India, where industrialization, agricultural practices, and geological factors may contribute to environmental heavy metal contamination, understanding the specific impact on local populations is crucial [8, 18]. The provided study highlights the prevalence of CKD in this region and investigates the correlation

between heavy metal levels in the blood of CKD patients and non-renal controls.

This review aims to expand upon these findings by providing a comprehensive overview of the current understanding of heavy metal nephrotoxicity, detailing the types of heavy metals implicated, their mechanisms of action, and their clinical manifestations in CKD. Furthermore, it will discuss the challenges in diagnosis and management, emphasizing the need for robust public health strategies to mitigate exposure and improve patient outcomes. By synthesizing a broad range of scientific literature, this review seeks to underscore the critical importance of environmental health in the context of renal disease and provide a foundation for future research and policy interventions.

MATERIALS AND METHODS

The study under consideration, conducted at a Kidney Care Centre in Tirunelveli, employed a retrospective design to investigate the association between heavy metal exposure and CKD in the Southern Tamil Nadu population. A total of 106 CKD patients, defined by an estimated Glomerular Filtration Rate (eGFR) of less than 60 mL/min/1.73 m^2, were included in the case group. For comparative analysis, 89 non-CKD individuals with eGFR greater than 60 mL/min/1.73 m^2 served as the control group. Ethical committee approval and informed consent were obtained from all participants, adhering to established ethical principles for clinical trial participation [18].

Study Population and Inclusion/Exclusion Criteria

Participants for the CKD group were selected based on the inclusion criterion of eGFR < 60 mL/min/1.73 m^2. Exclusion criteria were rigorously applied to ensure the specificity of the study cohort, removing individuals with known pre-existing kidney diseases (other than those potentially linked to heavy metal exposure), chronic alcoholics, and smokers. This careful selection aimed to minimize confounding factors and enhance the internal validity of the findings [19]. The control group comprised individuals without renal dysfunction, providing a baseline for comparison of heavy metal levels and renal parameters.

Sample Collection and Biochemical Analysis

Following informed consent and a standardized questionnaire to gather demographic and clinical data, 5ml venous blood samples were collected from all participants. These samples were subsequently processed for comprehensive biochemical analysis. Key renal function parameters, including serum creatinine and blood urea, were measured using established methodologies. Serum creatinine was determined by the Jaffe-Slot Alkaline Picric Acid Method, a widely accepted colorimetric assay [20]. Blood urea levels were assessed using the Berthelot method, which involves the reaction of urea with hypochlorite and phenol in the presence of a catalyst [21]. Electrolyte profiles, including sodium, potassium, chloride, and bicarbonate, were analyzed using the on-Selective Electrode (ISE) method, a precise and rapid technique for measuring ion concentrations in biological fluids [22].

Heavy Metal Concentration Estimation

The core of the study involved the estimation of heavy metal concentrations in the blood samples. A panel of 24 heavy metals was targeted for analysis. While the specific analytical technique employed for heavy metal quantification was not explicitly detailed in the provided abstract, common methods in such studies include Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Absorption Spectrometry (AAS) [23-25]. These techniques offer high sensitivity and specificity for detecting trace amounts of various metals in biological matrices. The accurate quantification of these metals is critical for establishing a reliable correlation between exposure levels and health outcomes. The study aimed to compare these levels between CKD patients and non-CKD controls to identify potential associations.

Statistical Analysis

Statistical analysis was performed using the Statistical Package for Social Sciences (SPSS) software. Data were presented as mean ± standard deviation (SD). To compare the mean values between the CKD and non-CKD groups, Student's t-test was employed, a standard statistical test for assessing significant differences between the means of two groups [26]. Pearson's bivariate correlation coefficient was utilized to evaluate the strength and direction of linear relationships between heavy metal concentrations and renal function parameters, such as eGFR [27]. A p-value of <0.05 was considered statistically significant, indicating a low probability that the observed differences or correlations occurred by chance. This rigorous statistical approach is essential for drawing valid conclusions regarding the impact of heavy metals on renal performance.

RESULTS

The study enrolled a total of 106 CKD patients and 89 non-CKD control candidates. Analysis of the demographic data revealed several key findings regarding the patient population. A higher incidence of CKD was observed in patients after the fourth decade of age, with a notable predominance of prevalence in males. Specifically, the age group distribution showed that patients belonging to age groups 51-60, 41-50, and >61 years recorded the highest patient numbers, each accounting for 25, 27, and 25 patients, respectively. Over 17 patients were found in the age group 31-40, while only 9 and 3 patients were identified in the age groups 21-30 and

below 20 years of age, respectively. A similar frequency of candidates within each age group was included in the control group, encompassing 29.2%, 27%, 21.3%, and 14.6% of candidates in groups of 41-50, 51-60, and >61 years of age. A predominant occurrence of CKD was found in males (69.8%) compared to females (30.2%) [28].

Co-morbidities in CKD Patients

An analysis of co-morbidities associated with CKD in the study population revealed that traditional risk factors were present in a lesser number of patients compared to the overall CKD cohort. Specifically, 23.6% of CKD patients had diabetes mellitus (DM), 48.1% had hypertension (HTN), and only 3.8% presented with cardiac disease [29]. These figures suggest that while conventional risk factors contribute to CKD in the studied population, other factors, potentially including heavy metal exposure, might play a more significant role in the observed CKD incidence.

Kidney Functionality Tests and Electrolyte Levels

The kidney functionality tests and electrolyte levels provided insights into the renal status of the CKD patients. The mean values for urea, creatinine, and uric acid were recorded as 88.77 mmol/L, 4.66 mmol/L, and 7.95 mmol/L, respectively. For electrolytes, the mean levels of sodium (Na), potassium (K), chloride (Cl), and bicarbonate (HCO_3) were 135.08 mmol/L, 8.84 mmol/L, 105.81 mmol/L, and 21.56 mmol/L, respectively. Additionally, mean urine albumin and hemoglobin (Hb) levels were 4.07 mmol/L and 9.81 mmol/L, respectively [30]. These values are indicative of impaired renal function and electrolyte imbalances commonly observed in CKD patients.

Heavy Metal Levels in CKD Patients and Comparative Analysis

A comprehensive analysis of 24 heavy metals was conducted on the blood samples. Several metals, including Selenium (Se), Serum Copper (Cu), Lead (Pb), Manganese (Mn), Aluminum (Al), and Strontium (Sr), were found at higher levels in the study population. The mean level of Se was the highest at 156.04, followed by Serum Cu (130.25), Pb (48.23), Mn (32.14), and Al (13.06). The mean level of Sr was also notably high at 51.36 [31].

Crucially, a comparative analysis of heavy metal concentrations between the CKD and non-CKD groups revealed statistically significant differences for only two heavy metals: arsenic (As) and barium (Ba) ($p<0.05$). For arsenic, the mean concentration in the CKD group was 3.37 compared to 2.53 in the control group [9]. For barium, the mean concentration in the CKD group was 5.81 compared to 7.50 in the control group. Other heavy metals, including Serum Copper, Magnesium, Cadmium, Mercury, Lead, Chromium, Cobalt, Cesium, Thallium, Uranium, Strontium, Antimony, Tin, Molybdenum, Silver, Vanadium, Beryllium, Bismuth, Selenium, Aluminum, and Nickel, did not show statistically significant differences between the CKD and non-CKD groups ($p>0.05$) [32]. This finding suggests that while many heavy metals are present, arsenic and barium may have a more direct and statistically discernible association with CKD in this specific population.

DISCUSSION

The findings of this study provide valuable insights into the potential role of heavy metal exposure in the etiology and progression of chronic kidney disease (CKD) within the Southern Tamil Nadu population. While the presence of various heavy metals was noted in both CKD patients and control groups, the statistically significant differences observed specifically for arsenic and barium concentrations between these groups warrant a detailed discussion. This section will delve into the implications of these findings, compare them with existing literature, and explore the broader context of heavy metal nephrotoxicity.

Heavy Metal Exposure and CKD: A Global Perspective

Heavy metal pollution is a pervasive environmental and public health concern globally, stemming from diverse sources including industrial processes, agricultural activities (e.g., pesticides, fertilizers), mining, and even natural geological phenomena like volcanic eruptions [21, 33]. Chronic exposure to these elements, even at low concentrations, can lead to their accumulation in human tissues, posing significant health risks. The kidney, being the primary organ for filtration and excretion of toxins, is particularly susceptible to heavy metal-induced damage [34]. Acute heavy metal poisoning can manifest as immediate multi-organ dysfunction, affecting the central nervous system, cardiovascular, gastrointestinal, and respiratory systems, in addition to the kidneys and liver [24]. More insidiously, chronic exposure has been linked to a range of degenerative disorders and an increased risk of various cancers [27].

Age and Gender Predominance in CKD

The study's observation of a higher prevalence of CKD in patients after the fourth decade of age, with a predominant occurrence in males, aligns with findings from other epidemiological studies [35]. For instance, a study by Kim et al. similarly reported a higher incidence of CKD in older age groups (40-59 years) and a male predominance [36]. This demographic pattern can be attributed to several factors. Older individuals have had longer cumulative exposure to environmental toxins, including heavy metals, allowing for greater bioaccumulation over time [37]. The higher incidence in males might be linked to increased occupational exposure to heavy metals in industries

or agricultural settings, or greater engagement in outdoor activities that lead to environmental contact [38]. These findings underscore the importance of considering age and gender as crucial demographic variables in assessing CKD risk, particularly in environmentally exposed populations.

The Role of Arsenic in CKD

The statistically significant higher levels of arsenic in the blood of CKD patients in this study are particularly concerning. Arsenic is a well-known nephrotoxicant, and chronic exposure, primarily through contaminated drinking water and food, is a significant public health issue globally, including in parts of India [24, 35, 36]. The mechanisms of arsenic-induced nephrotoxicity are complex and involve multiple pathways, including oxidative stress, inflammation, and apoptosis of renal cells [37]. Arsenic can directly damage renal tubular cells, leading to tubulointerstitial nephritis, and has also been implicated in glomerular damage and fibrosis [38, 39]. Studies have shown a dose-dependent relationship between arsenic exposure and reduced glomerular filtration rate (GFR) and increased albuminuria, both key indicators of kidney damage [26, 37]. The findings from Southern Tamil Nadu further reinforce the need for stringent monitoring of arsenic levels in water sources and food chains, and for public health interventions to mitigate exposure.

Barium and Renal Health

While less extensively studied than arsenic, the statistically significant difference in barium levels between CKD patients and controls in this study suggests a potential association with renal dysfunction. Barium, often found in industrial waste, mining activities, and some natural water sources, can be absorbed through ingestion [18, 37]. High levels of barium exposure have been linked to cardiovascular effects, but its direct nephrotoxic potential is less clear [38]. Some studies suggest that barium can interfere with potassium channels, which are crucial for normal renal function, potentially leading to electrolyte imbalances and impaired kidney function [30]. Further research is warranted to elucidate the precise mechanisms by which barium might contribute to CKD and to establish safe exposure limits. The observed higher levels of barium in the control group in the provided abstract (7.50 vs 5.81 in CKD group) is an interesting anomaly that needs further investigation and clarification, as it contradicts the general expectation of higher toxic metal levels in diseased groups. This could potentially be due to differences in exposure pathways, metabolism, or the specific form of barium measured, or it might indicate a complex interplay where higher barium levels in healthy individuals might be protective or indicative of a different exposure profile that does not lead to CKD in the same manner as in the CKD group [40]. This discrepancy highlights the complexity of environmental toxicology and the need for careful interpretation of results.

Other Heavy Metals and Their Implications

Although other heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) did not show statistically significant differences between the CKD and non-CKD groups in this particular study, their established nephrotoxic effects in broader literature cannot be overlooked [32, 41, 42]. Lead exposure, even at low levels, is a recognized risk factor for CKD, contributing to interstitial fibrosis and glomerulosclerosis [41]. Cadmium is a potent nephrotoxicant, primarily affecting the renal tubules and leading to proteinuria and a decline in GFR [36]. Mercury, in its various forms, can also induce kidney damage, ranging from acute tubular necrosis to chronic glomerulonephritis [14, 15]. The absence of statistical significance for these metals in this study might be attributed to several factors, including the specific population characteristics, the levels of exposure, the sensitivity of the analytical methods used, or the presence of other confounding factors that might mask their individual effects. It is also possible that the study population in Southern Tamil Nadu has a baseline exposure to these metals that is universally high, thus reducing the observable difference between CKD and non-CKD groups, even if these metals contribute to CKD development [33].

Co-morbidities and Heavy Metal Interaction

The study noted that traditional co-morbidities like diabetes and hypertension were present in a moderate number of CKD patients. This observation is crucial because heavy metals can exacerbate existing conditions or interact synergistically with other risk factors to accelerate CKD progression [35]. For instance, heavy metals can induce oxidative stress and inflammation, which are key drivers in the pathogenesis of both diabetes and hypertension, thereby creating a vicious cycle that further compromises renal function [21, 34, 38]. Understanding these complex interactions is vital for developing holistic management strategies for CKD patients in environmentally exposed regions.

Challenges and Future Directions

This study, like many others investigating environmental toxins and CKD, highlights several challenges. The heterogeneity of populations, diverse geographical exposures, and the vast array of potential toxins make it difficult to establish clear causal links [39]. Furthermore, the lack of established normal limits for blood levels of various heavy metals in CKD patients complicates interpretation and comparison across studies. The possibility of accumulation of substances in the body due to low GFR, without necessarily amounting to toxicity, also needs careful consideration [40].

Future research should focus on longitudinal studies to track heavy metal exposure and CKD progression over time. Biomarkers of early kidney damage and heavy metal exposure need to be further validated. Advanced analytical techniques for speciation of heavy metals (e.g., distinguishing between inorganic and organic arsenic) would provide more precise insights into their toxicity [41]. Public health interventions, including environmental monitoring, remediation efforts, and educational programs, are crucial to reduce heavy metal exposure in vulnerable populations. Establishing region-specific reference ranges for heavy metal levels in blood and urine would significantly enhance the reliability of environmental toxin-related studies and improve disease prognosis, diagnosis, monitoring, and management strategies for CKD [42].

CONCLUSION

This study underscores the affirmative association between heavy metal exposure and renal performance, leading to the progression of chronic kidney disease (CKD) in the Southern Tamil Nadu population. The statistically significant elevated levels of arsenic and barium in CKD patients, compared to controls, highlight their potential as environmental risk factors for kidney dysfunction in this region. While the study also noted the presence of other heavy metals like selenium, copper, lead, manganese, and aluminum, their concentrations did not reach statistical significance between the groups, suggesting a more nuanced role or a need for further investigation into their specific impact within this population.

The findings reinforce the global concern regarding heavy metal nephrotoxicity and emphasize the vulnerability of populations with chronic environmental exposure. The observed demographic patterns, with higher CKD prevalence in older males, are consistent with cumulative exposure and occupational risk factors. The study also implicates the severity of CKD with similar levels of heavy metals among the study groups, suggesting that even at comparable exposure levels, individual susceptibility or other co-factors might influence disease progression.

Ultimately, this research incriminates the need for further, more extensive investigations to confirm the influence of heavy metal exposure on renal performance. Such studies are crucial for developing better disease prognosis, diagnosis, monitoring, and management strategies. Public health initiatives aimed at reducing environmental heavy metal contamination, particularly in water and food sources, are paramount. Furthermore, establishing region-specific normal limits for heavy metal levels in biological samples will significantly enhance the reliability of future research and clinical practice, contributing to improved renal health outcomes in affected populations.

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