

# Associations of Airborne and Dermal Toxic Metal Exposures with Internal Metal Burden Among Firefighters

Quanjiang Li<sup>1</sup>, Dejian Lai<sup>1</sup>, Yongjun Gao<sup>2</sup>, Jooyeon Hwang<sup>1\*</sup>

1. School of Public Health, University of Texas Health Science Center at Houston; 2. University of Houston

## Introduction

Firefighters are exposed to mixtures of toxic metals during and after firefighting. These metals may be present in airborne particles or deposited on skin, turnout gear, and firefighting equipment, creating multiple potential exposure pathways. Urine measurements reflect internal metal burden, whereas skin wipes and air samples characterize surface contamination and airborne exposure. Relationships among these measurements remain incompletely understood. Evaluating them together may improve exposure assessment and help identify opportunities to reduce occupational exposure.



**Main aim:** To our knowledge, this is the first study to simultaneously examine associations of urinary metal concentrations with those in skin wipe and fireground air samples.

## Methods

We obtained data from the Texas Firefighter Cancer Study (TFCS), with samples collected by the research team at participating fire departments in Texas. The study included 35 firefighters sampled across multiple fire events, yielding 75 observations. We analyzed 24 metal(loid)s in urine (ng/mL), skin wipe samples (ppb), and air samples (µg/m<sup>3</sup>).

Values below the analytical limit of detection (LOD) were replaced with LOD/2. Shapiro–Wilk tests and Q–Q plots were used to assess distributions. Spearman correlations were calculated between different metals within each sample type and for the same metal across sample types because most concentrations were non-normally distributed.

Multiple linear regression models used natural log-transformed (log<sub>e</sub>) urinary metal concentrations as outcomes. Wipe and air concentrations for the same metal were retained simultaneously in every estimable model. Candidate covariates included BMI, race, smoking status, alcohol drinking frequency, smoked-food consumption within the past three days, firefighter rank, years of fire service, and weekly hours of fire exposure. Covariates were selected using stepwise selection based on the Akaike Information Criterion (AIC). Models used complete observations for the outcome, both predictors, and required covariates, so sample sizes varied by element. Models were not estimated when urinary concentrations lacked sufficient variability.

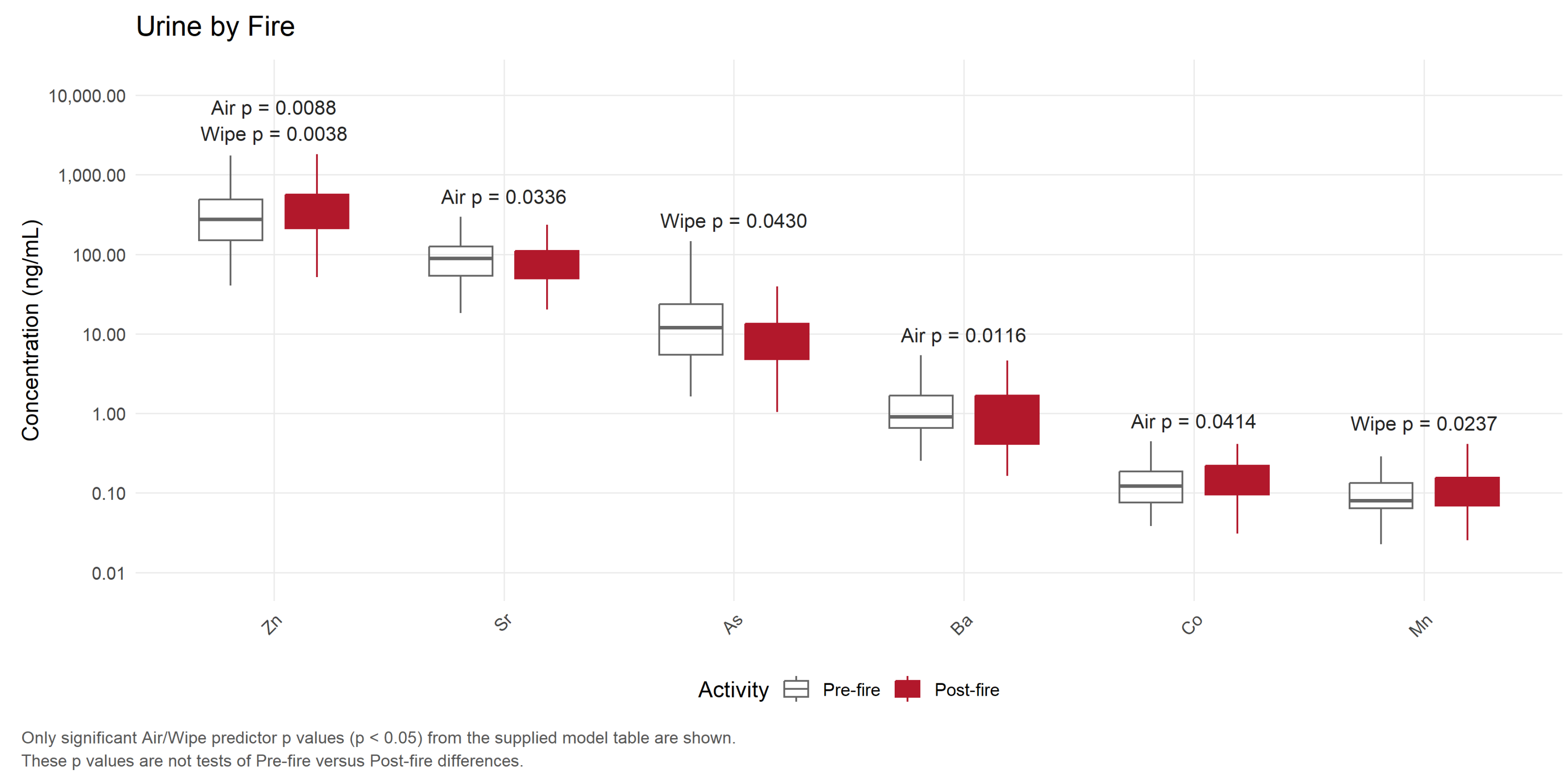
$$\ln(Urine) = \beta_0 + \beta_1 Wipe + \beta_2 Air + \gamma^T C + \varepsilon$$

Urine, Wipe, and Air represent concentrations of the same metal in the three sample types; C denotes the selected demographic, behavioral, and occupational covariates.

## Results

The study included 35 firefighters. The mean age was 40.1 years (SD = 8.01), and the mean body mass index was 29.7 kg/m<sup>2</sup> (SD = 3.65). The mean duration of fire service was 14.3 years (SD = 8.23), and the mean weekly fire exposure was 2.19 hours (SD = 1.35).

Metal concentrations varied across elements and sample types. Mean Zn concentrations were 423.53 ng/mL in urine, 4,064.68 ppb in wipe samples, and 40.63 µg/m<sup>3</sup> in air samples. Concentrations were right-skewed, especially in wipe and air samples. Wipe Fe averaged 21,182.43 ppb and reached 124,345.13 ppb.



Boxplots show pre- and post-fire urinary metal concentrations. Only significant Air/Wipe predictor p values from the multivariable regression models are shown; these are not tests of pre- versus post-fire differences.

Air metal concentrations were significantly associated with urinary Ba, Sr, Co, and Zn, while wipe concentrations were significantly associated with urinary Mn, As, and Zn. A 1 µg/m<sup>3</sup> increase in air Co was associated with a 19.44% higher urinary Co concentration (p = 0.0414); the corresponding increase for Ba was 1.30% (p = 0.0116). Zn was the only metal significantly associated with both predictors (Table 1).

**Table 1. Significant associations of air and wipe metal concentrations with urinary metal concentrations and mean exposure concentrations**

| Metal (sample type) | β estimate (% change)    | p value       | Mean concentration (unit) |
|---------------------|--------------------------|---------------|---------------------------|
| Ba (Air)            | <b>0.01 (1.30%)</b>      | <b>0.0116</b> | 11.14 µg/m <sup>3</sup>   |
| Sr (Air)            | <b>0.0086 (0.86%)</b>    | <b>0.0336</b> | 12.63 µg/m <sup>3</sup>   |
| Co (Air)            | <b>0.18 (19.44%)</b>     | <b>0.0414</b> | 0.38 µg/m <sup>3</sup>    |
| Zn (Air)            | <b>0.0030 (0.30%)</b>    | <b>0.0088</b> | 40.63 µg/m <sup>3</sup>   |
| Mn (Wipe)           | <b>−0.00057 (−0.06%)</b> | <b>0.0237</b> | 607.03 ppb                |
| As (Wipe)           | <b>−0.0059 (−0.58%)</b>  | <b>0.0430</b> | 37.44 ppb                 |
| Zn (Wipe)           | <b>−0.00017 (−0.02%)</b> | <b>0.0038</b> | 4,064.68 ppb              |

Note. β values are unstandardized coefficients for natural log-transformed urinary concentrations. Percentage change = [exp(β) − 1] × 100%, per 1 µg/m<sup>3</sup> air or 1 ppb wipe increase. Both predictors were retained; covariates were selected using AIC. Orange bold: p < 0.05. Means summarize all available original worksheet values, including zeros (air n = 22; wipe n = 69), without additional LOD substitution; these are descriptive sample counts, not regression sample sizes. Effects in different units are not directly comparable.

## Results (continued)

Behavioral and occupational factors were also associated with urinary metal concentrations in firefighters. Table 2 summarizes the direction of these associations across models. For the covariate comparisons summarized in Table 2, alcohol drinking frequency showed positive coefficients in all nine models retaining this covariate. Years of fire service showed predominantly negative coefficients, whereas smoked-food consumption and weekly fire exposure hours showed predominantly positive coefficients.

**Table 2. Behavioral and occupational covariate associations across metal-specific models**

| Covariate                                        | Models retaining covariate, n | Predominant direction, n |
|--------------------------------------------------|-------------------------------|--------------------------|
| Alcohol frequency: highest vs reference category | 9                             | 9 positive               |
| Years of fire service                            | 8                             | 7 negative               |
| Smoked-food consumption                          | 10                            | 7 positive               |
| Weekly fire exposure hours                       | 7                             | 5 positive               |

Counts refer to models retaining each covariate after AIC selection. Positive and negative describe coefficient directions.

## Conclusion

- Air metal concentrations were positively associated with urinary Ba, Sr, Co, and Zn concentrations.
- Skin wipe metal concentrations were negatively associated with urinary Mn, As, and Zn concentrations. Zn showed associations with both sample types, but in opposite directions.
- Alcohol drinking frequency, smoked-food consumption, and weekly fire exposure hours showed predominantly positive associations with urinary metal concentrations, whereas years of fire service showed predominantly negative associations.
- These findings suggest element-specific relationships between external metal measurements and internal metal burden, supporting further investigation using combined air, skin wipe, and urine measurements.

## Acknowledgement

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