ARTICLE

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Using colorimetric wipes to characterize lead surface levels in lead-exposed construction workers' homes and vehicles

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BACKGROUND: Lead home investigations following the confirmation of a lead-poisoned child in the home require a lead-certified technician using an X-ray-fluorescence (XRF) portable analyzer, but XRFs are not always available. Colorimetric surface wipes that immediately change color on a gradient from yellow-to-red with lead could address this gap, but they have not been tested or utilized extensively in non-occupational settings.
OBJECTIVE: To understand the usability of colorimetric wipes in lead home investigations with different potential sources of lead.
METHODS: We collected 104 colorimetric wipes to assess lead levels on surfaces from nine homes and seven vehicles from lead-exposed construction workers living with children. Colorimetric wipe results ($n = 81$) were compared with inductively coupled plasma optical emission spectroscopy laboratory analysis.
RESULTS: Lead was detected on 46(58%) of home surface wipes, with highest percentage of red wipes from surfaces in kitchen, followed by entrance, living room, bedroom, and laundry room samples. For vehicle surface wipes, 17 (71%) detected lead, with the highest percent of red wipes in the trunk, followed by back and front seat areas. Wipe color readings were significantly and positively correlated with laboratory analysis (Kendall's $\tau = 0.42$). At the 18 µg/sample threshold (i.e., level at which the wipe is expected to turn pink/red), the method showed high specificity (87%), moderate accuracy (78%), high negative predictive value (87%), and low false positive rate (13%). Of the wipes above 10 µg/sample public-health lead guideline, 80% changed color, suggesting high sensitivity.
IMPACT:

- The dissemination of colorimetric wipes for lead home investigations can reduce costs and improve the immediate screening of lead dust-contaminated surfaces in residential settings. Colorimetric wipes proved invaluable in identifying sources from lead take-home and lead-in-paint in the homes and vehicles of lead-exposed construction workers.

Keywords: Surface wipes; Colorimetric wipes; Lead; Home; Vehicles; Construction workers

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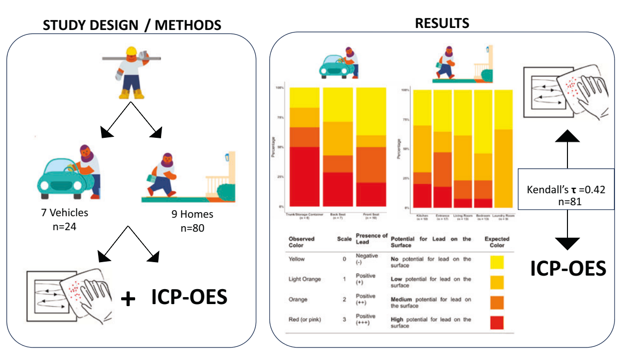
Graphical Abstract



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INTRODUCTION

Lead exposure in any amount can cause adverse health impacts, and the more significant the exposure, the greater the effect [1–3]. Children are more susceptible to lead exposure and poisoning than adults because they tend to engage in more hand-to-mouth behavior, and a more significant proportion of ingested lead accumulates in their bodies [4] Further, children's blood-brain barrier is less mature than that of adults, allowing the lead to enter the brain at a critical stage of neurological development [5, 6] Children exposed to lead, even in small amounts, can experience irreparable problems with physical and neurological development and behavioral issues [7, 8]. Since children spend considerable time at home, reducing lead dust on home surfaces is essential to lower their exposure to lead [9].

A typical method for assessing lead on surfaces in different microenvironments is to use a laboratory-certified wet wipe on a specified sample area, following standardized wiping instructions, and sending the wipe to the laboratory for lead confirmation [10, 11]. In occupational settings, wipe sampling, following National Institute for Occupational Safety and Health (NIOSH) method 9105, has been widely used to efficiently identify lead on surfaces in situ using a colorimetric method [10, 12–15], which essentially adds a step before sending to the laboratory to read the color change of the soiled wipes in the field. Following the use of a commercially available wipe kit developed by NIOSH [16], soiled wipe color develops in the presence of lead (i.e., reddish color suggesting lead). Color intensity is proportional to the amount of lead in the wipe, which has been confirmed under controlled laboratory and field conditions [12, 13]. Soiled wipes can also be sent to a laboratory for chemical analysis of various elements, including lead. However, workplaces usually have much higher levels of lead than homes. Thus, it is unclear if these colorimetric wipes would be sensitive enough for lead home investigations.

Lead investigations in homes require a lead-certified technician using an expensive portable X-ray-fluorescence (XRF) analyzer, usually only performed after a confirmed child lead poisoning [17, 18]. The United States Department of Housing and Urban Development (HUD), Office of Healthy Homes and Lead Hazard Control [17, 19–21], has also recommended using standardized wipe sampling of surfaces to identify lead in dust from home surfaces. However, to our knowledge, method applications of the NIOSH-developed and validated colorimetric lead wipes outside the workplace have been scarcely used in the literature (e.g., Ahmid et al. [22]). Housing authorities currently do not recommend colorimetric wipes in their guidelines. Adopting a colorimetric step in lead wipe sampling in lead home investigations would help identify problem areas immediately, as wipe laboratory analyses may take weeks to report back to the families and can be expensive. Further, color techniques provide non-language-based compelling visuals that would facilitate education with families to reduce childhood lead exposure. Wipes are then recommended to be sent to the laboratory for confirmation.

In the present study, we aim to understand the usability of colorimetric wipes in lead home investigations with different potential sources of lead (e.g., lead paint, lead-exposed occupation of inhabitants). We hypothesized that the use of colorimetric wipes, as described in the occupational literature to identify the take-home pathway by identifying contamination problems in workplaces [13], may serve for identification of lead contamination in homes, for primary education, and to inform remediation efforts in homes of lead-exposed workers. The specific objectives of this study are to: 1) describe the use of colorimetric wipes to screen lead on surfaces of nine homes and seven vehicles of Boston-area families with someone working in a lead-exposed construction job and living with a child and 2) validate the use of wipes in a residential context (not occupational) by comparing to laboratory lead findings to give confidence in interpreting the color change in lead home investigations.

MATERIALS AND METHODS

Study design

A community-engaged exposure assessment research study, RECLEAN Pilot Study: Reducing Lead in the Homes of Construction Workers, was tailored for families of lead-exposed construction workers living with a child. To be the primary research participant, the construction worker had to be 18 years of age or older, work full time (≥ 35 h per week) in a construction job with high risk for metal exposures, live in the Greater Boston area of Massachusetts, live with at least one child one year of age or older (i.e., did not have to be a child of the worker but had to reside in the same household), and speak English or Spanish. A screening survey was performed before consent to select workers who performed renovations, bridge constructions, welding or metal work, demolition, or were known to be exposed to lead at work. Workers were recruited with the assistance of nonprofit organizations serving underserved residents, such as the Massachusetts Coalition for Occupational Safety and Health (MassCOSH), New England Region Laborers' Health & Safety Fund of North America LiUNA TriFunds, and the Boston Medical Center's Pediatrics Lead Clinic. Each participant provided written consent after reviewing the informed consent form in their preferred language (English or Spanish), answered a few sociodemographic and work-related questions, and allowed us in their home to perform surface sampling. All study protocols were approved by the Boston Medical Center and Boston University Medical Campus Institutional Review Board.

Results from the colorimetric wipes were communicated to the family during the visits, and resources were immediately provided to families for remediation and follow-up. However, this publication solely focuses on the data from the surface wipe samples. Remediation, not described in this publication, included educational and environmental interventions along with resources such as different products specialized to clean lead and referrals to organizations providing local services related to lead prevention (e.g., health insurance access, lead clinic follow-up).

Surface wipe sampling

Wipe samples were collected during one field visit in eight homes and a repeated visit in one home in 2021 and 2022. When scheduling the visit to a home, we asked participants to refrain from vacuuming the home, as possible, at least one week before the scheduled home visit to allow for ample dust deposition for our tests.

We used the SKC (Eighty Four, PA) Full Disclosure Wipe Kit, part number 550-002 (SKC, 2025a) [16]. To collect samples, we used a disposable template 1 ft by 1 ft (0.3 m by 0.3 m, SKC part number 225-2416) to demarcate the sampling area and wiped the area with a gloved hand following the wiping pattern described in the residential methods for surface sampling [20, 23] This procedure meets the NIOSH Method 9105 for lead in dust wipes and conforms to the American Society for Testing and Materials (ASTM) International E1792 [15, 24]. The detailed colorimetric surface wipe protocol used is described in Supplemental Materials Appendixes A, B. An immediate color response for the presence of lead was confirmed by a reddish color developing on the wipe. According to the wipe manufacturer, the wipe is likely to turn pink or red if lead exceeds 18 µg per sample [16], hereinafter referred to as "red". Controlled laboratory [10] and industrial hygiene workplace evaluations [13] of the colorimetric wipes documented a gradient color response proportional to the amount of lead in the sample, with the color change going from negative (yellow) to positive (orange or red). The manufacturer also reports that other elements may interfere with color change from the presence of lead (i.e., silver, cadmium, barium, mercury, titanium) [16].

The workers' homes and vehicles were surveyed to identify potential areas with lead. Besides the homes, worker vehicles were included as a documented pathway of lead contamination from the workplace to the home [25–27]. In homes, we focused on collecting samples from smooth surfaces that were likely to be contaminated by the worker and likely to expose other family members. Home areas included the kitchen, entrance, living room, bedroom, and laundry room. We also prioritized surfaces with risk for lead dust from paint, like windowsills and floors, considering the old stock of housing in the Boston area. Inside vehicles, we focused on the areas most used or touched by the worker. We sampled the driver seat and areas of the vehicle where the worker reported storing work items, typically the back seats and trunk. We also sampled children's seats in the

Table 1. Observed color scale or color reading categories for lead colorimetric wipes.

Observed Color	Scale	Presence of Lead	Potential for Lead on the Surface[a]	Expected Color
Yellow	0	Negative (-)	No potential for lead on the surface	
Light Orange	1	Positive (+)	Low potential for lead on the surface	
Orange	2	Positive (++)	Medium potential for lead on the surface	
Red (or pink)	3	Positive (+++)	High potential for lead on the surface	

[a]Color change from yellow to red/pink denotes the potential presence of lead likely at levels above the manufacturer-reported threshold of 18 µg in a wipe sample.

back seats, if any were in the vehicle. Sample location descriptions were noted and photographed.

Following manufacturer instructions, within three minutes of color development, we performed visual field qualifications by at least two researchers in the field. The observed color was categorized from 0 (yellow) to 3 (red) using the scale shown in Table 1.

For quality control, we routinely collected positive control wipes using a lead figurine that turned wipes red to verify that the kit worked as expected. We also collected field blanks (unused wipes with and without solution) and media blanks (new wipes) for each home/vehicle sample set. To optimize and standardize color results and for quality control we only used the colorimetric solutions within the same day of preparation.

Wipe samples laboratory analysis

After color assessment in the field, the wipe samples were placed in clean plastic containers and shipped at room temperature to the Soil, Water and Environmental Laboratory at the Ohio State University, Columbus, Ohio. Total elemental content in the wipe samples was determined using microwave-assisted acid digestion according to the EPA Method 3051a [28], in which 0.5 g of sample was digested in 50 mL of nitric and hydrochloric acid in a microwave (CEM Corporation, Matthews, NC). The total elemental content in wipes was also determined according to EPA Method 3051a but with the entire wipe digested. Digestion solutions were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) according to EPA Method 6010D [29] with an Agilent 720 ICP-OES (Agilent Technologies, Santa Clara, CA). Quality control measures included measurements using a soil reference material CRM 059-050 G with known elemental content from Honeywell Fluka International (Charlotte, NC), reagent blanks, wipe blanks, and recovery controls using spiked samples. A total of six additional elements were measured to aid in determining potential interference in the color reading, including aluminum, cadmium, chromium, copper, nickel, and zinc, with reporting limits (RL) listed in Supplemental Material Table S1. Specifically for lead, RL was 1 µg/sample.

Data analysis

Laboratory analysis results were blank corrected for zinc because of contamination from the wipe solutions tested in the quality control samples. Given that most samples (62%, Table S1) were above RL for lead and the lab provided an estimated value for <RL, we used the lab-provided values, although acknowledging that values < RL had lower accuracy.

We compared the observed color of wipes among five key surface areas of the homes: entrance, kitchen, living room, bedroom, and laundry room. We also compared the color of wipes in three areas of the vehicles: the front seat (including steering wheel, dashboard, driver's/front passenger's seat and floor, etc.), back seat (including back passenger's seats and floor, child's vehicle seat, etc.), and trunk. We also further grouped home surfaces into broader categories for analysis, including wipes collected on windowsills, non-work-related surfaces, work-related surfaces, and floors, to relate to occupational and non-occupational origin sources and directly compare to existing guidelines. Non-work-related surfaces included areas where the worker did not store anything or were not windowsills. Work-related areas were defined as work items or where the worker stored work items (e.g., the surface of work boots, closet where work equipment was stored). Note that the number of wipes in the work-related group may be underestimated since we only included samples where we explicitly noted the presence of work items or were reported by the worker to be used to store work items.

To compare lead mass loading across more than two groups, we used the Kruskal-Wallis test. When statistically significant, we conducted Dunn's post-hoc pairwise comparisons with Bonferroni correction to adjust for multiple testing. For categorical comparisons, such as wipe color intensity categories (e.g., red vs. non-red, or yellow vs. orange/red), we used Fisher's Exact test.

Lead mass loading on surfaces obtained from the laboratory was compared to the field colorimetric analysis results. Kendall's rank correlation coefficient was used to compare lead loading results based on color versus mass reported by the laboratory from the wipes by surface area sampled. Lastly, lead mass loading on surfaces was also compared to existing health and safety guidelines for lead on surfaces [21, 30–32]. For statistical analyses, we used R (version 3.3.1); statistical significance was evaluated at $p < 0.05$.

RESULTS

Sociodemographic characteristics

The sociodemographic characteristics of the nine households of construction workers are shown in Table 2. Workers were primarily male (89%), Hispanic (89%), young (mean age of 34 years), with a high school degree or less (56%), and having at least one child less than 6 years of age at home (67%). Construction workers performed multiple duties, including painting, demolition,

Table 2. Sociodemographic characteristics of 9 participating construction workers, Greater Boston Area (2021-22).

Sociodemographic characteristics	Number (%)
Age (years)	
Mean (SD)	34 (9.4)
Median [Min–Max]	32 [24–54]
Missing	1 (11%)
Age Group	
20–29	3 (33%)
30–39	4 (44%)
40+	1 (11%)
Missing	1 (11%)
Sex	
Female	1 (11%)
Male	8 (89%)
Ethnicity	
Hispanic	8 (89%)
Non-Hispanic	1 (11%)
Education	
High school diploma or GED	3 (33%)
Less than a high school diploma or GED	2 (22%)
Some college but no degree	4 (44%)
Marital Status	
Married	3 (33%)
Separated	1 (11%)
Unmarried	3 (33%)
Missing	2 (22%)
Salary per Month	
Less than $2100	1 (11%)
$2100 to $3000	5 (56%)
$3000 or above	3 (33%)
Household Size	
Mean (SD)	5 (2)
Median [Min–Max]	5 [3–9]
Has children under 6 years old	Yes 6 (67%) No 3 (33%)
Family Income	
Less than $35k	3 (33%)
$35k to $75k	3 (33%)
$75k or above	2 (22%)
Missing	1 (11%)

GED General educational development diploma or a high school equivalency diploma.

remodeling/renovation, masonry, sanding/scraping, dry walling, and installing pipes and cables.

Color readings and lead mass loadings in different areas

Table 3 provides descriptive statistics of the observed color readings in the wipes for the homes and vehicles of the nine households. We collected 80 colorimetric wipes in nine homes and 24 wipes in seven vehicles, for a total of 104 wipes. Of the home wipes, 58% showed color changes (from yellow to orange or red), while 71% of vehicle wipes showed color changes, indicating the presence of lead in the homes and vehicles of construction workers.

Table 3. Observed color reading and lead mass loading on surface wipes in homes and vehicles of construction workers in the Greater Boston Area (2021–22).

Household	Home: Count of total wipes	Home: Count (percentage) of red wipes[a]	Home: Count (percentage) of red/orange wipes[a]	Home: Median (range) of detected lead in µg/sample	Vehicle: Count of total wipes	Vehicle: Count (percentage) of red wipes[a]	Vehicle: Count (percentage) of red/orange wipes[a]	Vehicle: Median (range) of detected lead in µg/sample
1	7	0 (0%)	6 (86%)	3.1 (1.0–146)	3	2 (67%)	3 (100%)	77.3 (15.1–102)
2	3	1 (33%)	2 (67%)	3.3 (<1–9.8)	2	1 (50%)	1 (50%)	4.4 (<1–8.3)
3	5	0 (0%)	4 (80%)	10.6 (<1–50.2)	3	0 (0%)	3 (100%)	4.9 (<1–29.6)
4	10	1 (10%)	9 (90%)	6.7 (<1–109)	—	—	—	—
5	11	5 (46%)	10 (91%)	14.1 (<1–90.7)	3	1 (33%)	3 (100%)	7.2 (6.6–8.3)
6	16	1 (6%)	3 (19%)	0.5 (<1–40.3)	7	1 (14%)	1 (14%)	0.3 (<1–7.7)
7	7	0 (0%)	2 (29%)	1.4 (<1–29.0)	—	—	—	—
7*	5	0 (0%)	5 (100%)	1.3 (<1–2.6)	—	—	—	—
8	8	0 (0%)	3 (38%)	**	4	2 (50%)	4 (100%)	**
9	8	2 (25%)	2 (25%)	**	2	0 (0%)	2 (100%)	**
Total	80	10 (13%)	46 (58%)	2.0 (<1–146)	24	7 (29%)	17 (71%)	6.6 (<1–102)

-These households did not own a vehicle.
*Household second visit.
** No results are available from the samples of these households due to laboratory issues.
[a]Red/orange wipes include all samples with color changes to orange, pink, or red. Red wipes are a subset of the total of red/orange wipes.

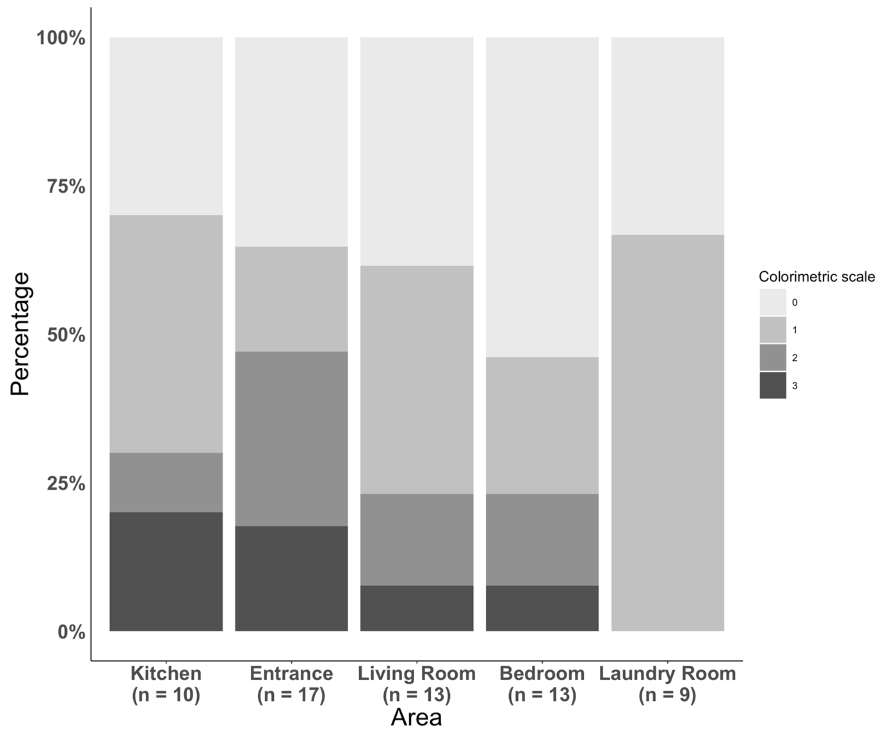

Fig. 1 Percentage of observed color readings of surface wipe samples for different areas in nine homes of construction workers in the Greater Boston area (2021–22). Yellow means no lead, light orange means low lead potential, orange means medium lead potential, and red indicates high likelihood of lead; *n* as the number of samples.

Table 4. Observed color readings and lead mass loadings on surface wipes in construction workers' homes and vehicles.

Location	Count (percentage) of red wipes[c]	Count (percentage) of red/orange wipes[c]	Median lead (μg/sample)	Geometric mean lead (μg/sample)	Range of lead (μg/sample)
Homes					
Kitchen ($n = 10$)	2 (20%)	7 (70%)	2.9	1.9	<1–15.7
Entrance ($n = 17$)	3 (18%)	11 (65%)	6.5	2.1	<1–26.1
Living room ($n = 13$)	1 (8%)	8 (62%)	8.5	6.7	<1–90.7
Bedroom ($n = 13$)	1 (8%)	6 (46%)	3.1	2.9	<1–32.4
Laundry room ($n = 9$)	0 (0%)	6 (67%)	0.8	1.8	<1–146
	$p = 0.687$[a]	$p = 0.817$[a]	$p = 0.470$[b]		
Vehicles					
Truck/storage container ($n = 6$)	3 (50%)	5 (83%)	7.7	3.6	<1–15.1
Back seat ($n = 7$)	2 (29%)	5 (71%)	3.5	2.1	<1–29.6
Front seat ($n = 10$)	2 (20%)	6 (60%)	4.2	3.1	<1–102
	$p = 0.449$[a]	$p = 0.846$[a]	0.930[b]		

n = Number of samples. Only matching color and mass loading data were included. Results did not include data from 2 of the 9 households due to laboratory issues.

[a]Fisher's Exact Test was used to compare the proportion of red and red/orange wipes across locations.

[b]Kruskal-Wallis Test was used to compare lead mass loadings across locations.

[c]Red/orange wipes include all samples with color changes to orange, pink, or red. Red wipes are a subset of the total of red/orange wipes.

Comparing the percentage of wipes that changed colors in five areas of the homes, the kitchen ranked first, followed by the entrance, living room, bedroom, and laundry room (Fig. 1). In the kitchen, 20% of the wipes showed red and 70% had color changes (i.e., orange or red). In addition to floors and windowsills, wipes were collected from a variety of other surfaces within each area of the home. For example, in kitchens, surfaces such as countertops and a breakfast bar were sampled; in entrances, door handles/knobs, shoes racks were included. In living rooms, sampling included surfaces like tables and children's toys, while in bedrooms, baseboard heaters, baby cribs, and cloth/shoes were wiped. In laundry rooms, wipes were taken from the tops and inner areas of appliances. Table 4 also includes the median, geometric mean (GM), and range of lead mass loading for the

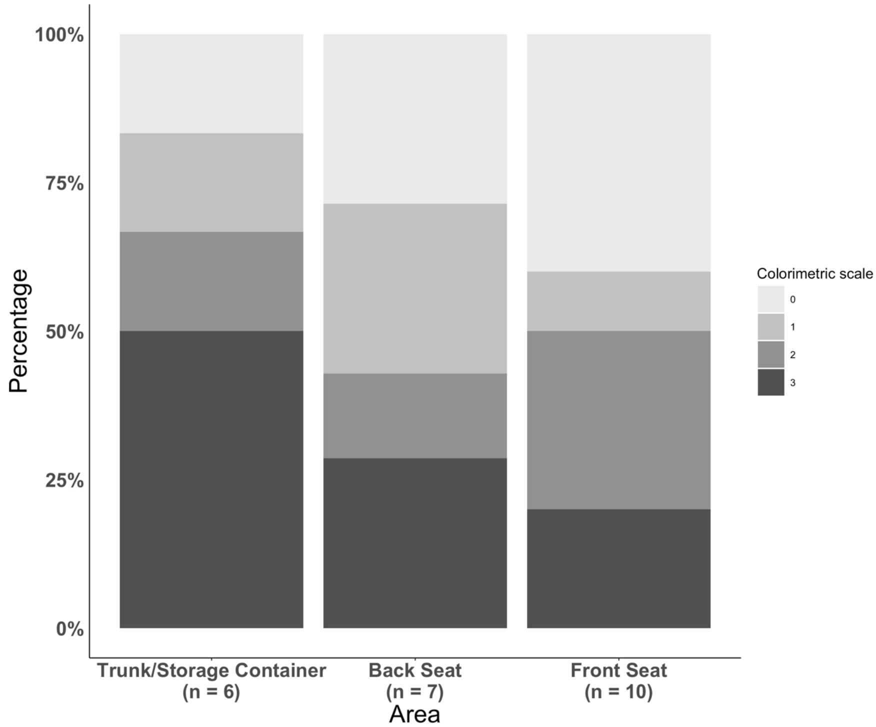

Fig. 2 Percentage of observed color readings of surface wipe samples by different areas in seven vehicles of construction workers in the Greater Boston area (2021–22). Yellow means no lead, light orange means low lead potential, orange means medium lead potential, and red represents a high likelihood of lead; *n* as the number of samples.

different areas, with the living room having the highest central tendencies (median of 8.5 µg/sample, GM of 6.7 µg/sample). The highest surface mass loading measured in the wipe samples in the home was found in one of the laundry rooms (146 µg/sample). However, no statistically significant differences were found in the percentages of observed color readings or lead mass loadings between different areas in the homes.

For the vehicles, the trunk had the highest percentage of wipes that changed color, followed by the back seat and front seat (Fig. 2). Trunk/Storage container area included sampling of surfaces in the trunk and any work items stored in the trunk. Back seat included surfaces on the back seats of the vehicle and in one children's vehicle seat. Front seat included surfaces from the driver seat, steering wheel, door handles, and shift. Fifty percent of the wipes showed red in the vehicle trunks, while 83% had color changes (Table 4). Wipes obtained from the vehicle trunk surfaces also showed the highest lead results in their measured central tendencies (median of 7.7 µg/sample, GM of 3.6 µg/sample), followed by the front seat (median of 4.2 µg/sample, GM of 3.1 µg/sample) and then the back seat (median of 3.5 µg/sample, GM of 2.1 µg/sample). However, the highest lead mass loading measured in a surface wipe was in the front seat area (i.e., dashboard) of one of the vehicles (102 µg/sample). No statistically significant differences were found in the percentages of observed color readings or lead mass loadings between vehicle areas.

Color readings and lead mass loadings by surface category

Table 5 describes the observed color readings and lead mass loadings from surface wipes in construction workers' homes, categorized by four types of surfaces (i.e., windowsill, non-work-related, work-related, and floor surfaces). We found no significant difference in the observed color readings between the groups. Lead mass loading differed significantly across surface categories (Kruskal-Wallis $\chi^2 = 16.91$, $p < 0.001$). The highest median lead concentration was found on windowsills (14.2 µg/sample), followed by floors (6.8 µg/sample), work-related surfaces (1.8 µg/sample), and non-windowsill surfaces (0.59 µg/sample). Post-hoc pairwise comparisons using Dunn's test with Bonferroni correction showed that both windowsills ($p = 0.003$) and floors ($p = 0.014$) had significantly higher lead levels than non-windowsill surfaces. No other pairwise differences were statistically significant.

Comparison of laboratory analysis and colorimetric results

The distribution of mass loadings in the surface wipes, quantitatively obtained from the laboratory for lead and other elements measured, and their distributions are shown in Supplemental Materials Fig. S1 and Table S1. We compared the lead mass loading from the laboratory analysis results with the colorimetric results and found that the two methods were statistically significantly correlated (Kendall's $\tau = 0.42$). The comparison of the laboratory analysis results by color change categories can be also visually observed in Fig. 3.

We evaluated the agreement between the color response and laboratory findings, assuming that the laboratory correctly identified the presence or absence of lead. Figure 3 and Table S2.1 compare the observed color response and the measured lead mass loading, in comparison with the manufacturer-reported level of 18 µg/sample (equivalent to 18 µg/ft^2 or 1.94 µg/m^2 for our sampling protocol) at which the wipe is expected to change color to pink/red. When evaluating performance at the manufacturer-specified threshold of 18 µg/sample, specificity was high (87%), accuracy was moderate 78%, and the false positive rate was only 13%. Although only 31% of wipes turned pink or red at this level, indicating lower sensitivity, most color-changing wipes below 18 µg/sample still contained measurable lead. In fact, 63% of these had loadings between <1 and 5 µg/sample (median: 2.59 µg/sample). Only 14 wipes (27%) showed a color change without detectable lead, suggesting that relatively few unconfirmed true (pink/red) positives were found. We also compared the results related to the laboratory detection limit (1 µg/sample) (Fig. 3 and Table S2.2). Among samples with lead concentrations above the

Table 5. Observed color readings and lead mass loadings from surface wipes in construction workers' homes by four types of surface categories: Non-work-related, windowsill, work-related, and floor surfaces[d].

	Non-work related Surfaces[d] ($n = 36$)	Windowsill Surfaces[d] ($n = 13$)	Work-related Surfaces[d] ($n = 4$)	Floor Surfaces ($n = 11$)
Count (percentage) of red wipes[f]	5 (14%)	2 (15%)	0 (0%)	1 (9%)
Count (percentage) of red/orange wipes	22 (61%)	9 (69%)	3 (75%)	7 (64%)
Median of detected lead in µg/sample[b]	<1[a,b,c]	14.2[a,c]	1.8[a]	6.8[a,b]
Geometric mean of detected lead in µg/sample	<1	8.80	2.95	7.95
Range of detected lead in µg/sample	<1–146	1.2–90.7	1.4–17.1	<1–109
Count (percentage) above HUD/EPA guideline[e]		0 (0%)		3 (27%)
Count (percentage) above EPA new standards[e]		2 (15%)		8 (73%)

n = Number of samples. Note: Only matching color and mass loading data were included. Results did not include data from 2 of the 9 households due to laboratory issues.
[a]Significant differences between all categories (Kruskal-Wallis Test, p-value < 0.001).
[b]Significant difference between two categories: non-work-related and floor surfaces (Dunn's Test, p-value = 0.014).
[c]Significant difference between two categories: non-work-related and windowsill surfaces (Dunn's Test, p-value = 0.003).
[d]No work-related surfaces include all surfaces except windowsills or surfaces confirmed by workers where work items were stored. Windowsill surfaces refer to surfaces on the frame of windows. Work-related surfaces included only surfaces explicitly confirmed as work-related surfaces (e.g., work shoes on the surface sampled) were included.
[e]HUD/EPA have established reference values for surface lead dust: 10 µg/ft^2 (equivalent to 10 µg/sample) for floors and 100 µg/ft^2 (equivalent to 100 µg/sample) for windowsills (HUD [17, 20, 33]; EPA [31] The most recent EPA update finalized a more stringent floor standard of 5 µg/ft^2 (equivalent to 5 µg/sample) and windowsill standard of 40 µg/ft^2 (equivalent to 40 µg/sample) [32].
[f]Red/orange wipes include all samples with color changes to orange, pink, or red. Red wipes are a subset of the total of red/orange wipes.

laboratory reporting limit of 1 µg/sample, 76% of wipes exhibited a color change (to orange, pink, or red), with a moderate precision of 73% and an overall moderate accuracy of 68%. These findings suggest the method is reliable in identifying the presence of low-level lead, even beyond manufacturer's threshold, and can help flag surfaces for further confirmation.

When comparing the results of surface wipes with existing health and safety home guidelines, we found that 27% of floor wipe samples (3 out of 11 samples) had lead mass loadings above the HUD guideline of 10 µg/ft^2. [17, 19, 20, 30, 31, 33] If compared with the newest guideline published by EPA in October 2024 [32], 8 (73%) floor wipe samples were above the guideline level (5 µg/ft^2). In contrast, no windowsill samples exceeded the HUD guideline of 100 µg/ft^2 (equivalent to 100 µg/sample for this study, or 1076 µg/m^2). [17, 20] However, 2 (15%) windowsill samples were above the newest published EPA guideline for windowsills, which is 40 µg/ft^2. In the absence of other guidelines for other locations or types of samples, we found that 9% ($n = 7$) of all samples (including wipes in homes and vehicles analyzed in the laboratory, $n = 81$) were above 40 µg/ft^2 (equivalent to 40 µg/sample or 430.5 µg/m^2), an older guideline level for lead hazards in home floors [17, 20]. Among those 7 samples, 71% ($n = 5$) changed color. In terms of the newest published guideline of 5 µg/ft^2 for lead hazards in dust on floors, of the 34 (42%) wipes (among all samples including homes and vehicles $n = 81$) above this guideline level, 25 (74%) changed color. Lastly, 4% ($n = 3$) of all samples (including homes and vehicles $n = 81$) were above 100 µg/ft^2, and among those samples, 67% ($n = 2$) changed color.

DISCUSSION

In this study, we demonstrated that colorimetric wipes could be used effectively in a residential environment, both because of the lead levels documented in homes with multiple potential sources of lead and because of the sensitivity of the wipes. The wipes were particularly good at detecting lead contamination on surfaces related to the lead take home pathway in the homes and vehicles of construction workers, specifically immediately flagging lead contamination in work items or surfaces where work items are usually stored. Also, colorimetric wipes were able to identify potential lead sources from painted surfaces such as windowsills even when the wipes manufacturer acknowledges the color response may not always work well on painted surfaces [16], likely because of potential color interferences from paint.

In terms of the surface levels of lead found in the homes investigated, although there are few comparable studies of construction workers, the entrance lead mass loadings we measured (GM = 2.1 µg/sample) were comparable to loadings found in an earlier study by Piacitelli et al. [25] in the homes of lead-exposed construction workers (GM = 2.1 µg/sample). In contrast, our highest lead mass loading in vehicles (GM = 11.7 µg/sample) was substantially lower than that found by Piacitelli et al. [25] (driver's floor GM = 102 µg/sample, passenger's floor GM = 42.7 µg/sample) and that reported in a Tennessee study with paint remediation workers' vehicles (mean of 40.3 µg/sample, Boraiko et al. [26]). We also collected one sample from a child vehicle seat surface made of cloth and plastic, with lower lead mass loading (0.5 µg/sample) compared to a previous study [27] (median of 98 µg/sample). No other vehicles in our study had child vehicle seats, so we were not able to sample a larger number to find a distribution of concentrations in children vehicle seats in our participants. Thus, lower levels in the present study could be related to secular trends in lead contamination or could be an artifact of the specific population included in each study considering the large variability typical of surface contamination.

We found that windowsill surfaces were statistically higher than work and non-work-related surfaces in the homes, and that surface lead contamination was spread throughout the different areas of

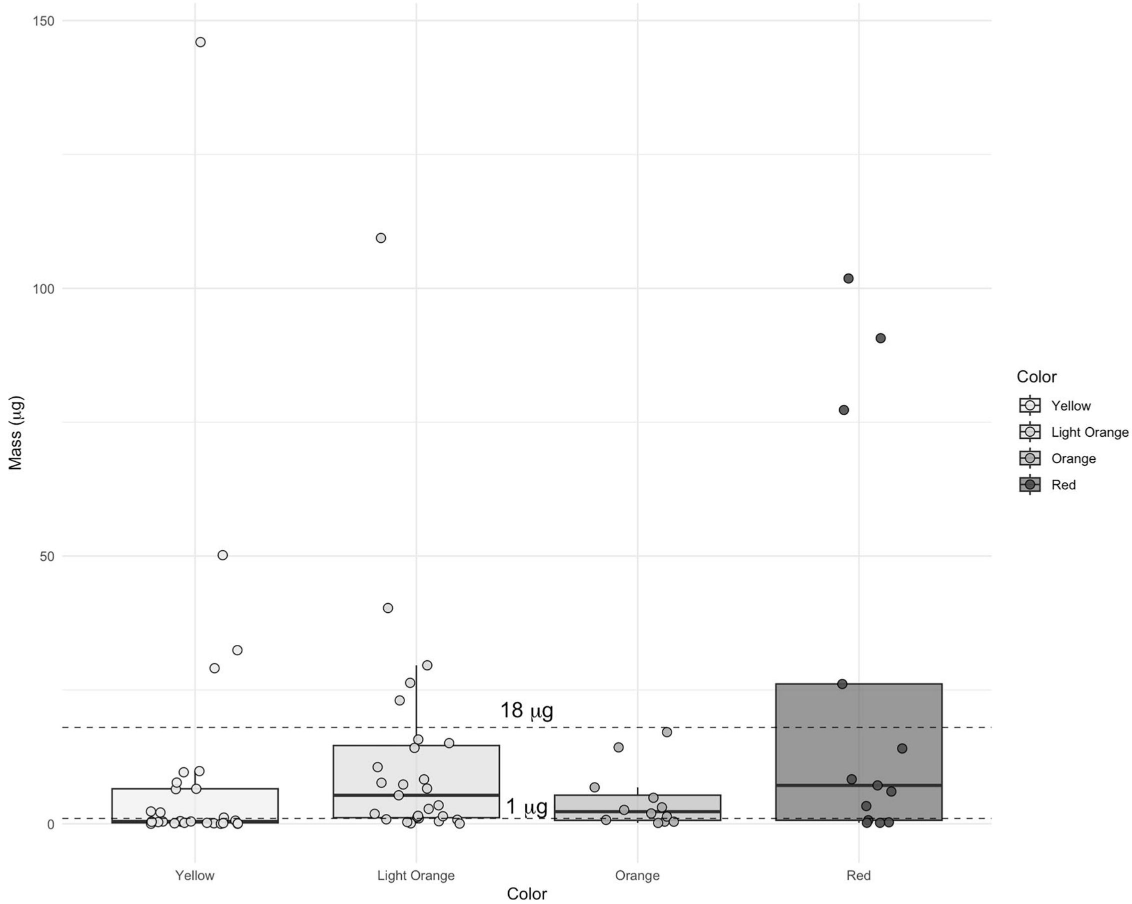

Fig. 3 Distribution of lead mass loading per area sampled (1 ft x 1 ft or 0.3 m × 0.3 m) comparing the different observed color responses on surface wipes against the manufacturer-reported level of 18 µg per sample, at which is likely to change color to red/pink, and the laboratory reporting limit of 1 µg per sample. Total surface wipes analyzed in the laboratory ($n = 81$), yellow ($n = 29$), light orange ($n = 27$), orange ($n = 12$), red ($n = 13$); n as the number of samples.

the homes and vehicles. Results suggest that differences per location were not necessary to indicate the need for remediation. Lead contamination findings in work-related areas suggest that lead paint is not the only lead source identified. Lead contamination found in work items or where work items were stored indicates that these workers were likely bringing lead from work. Thus, as Kalweit et al. [34] suggested, both take-home and lead-paint housing issues were likely co-occurring in these households, which points to overlapping vulnerabilities typical of these households. Having several lead sources in a home presents a challenge for lead prevention strategies. However, results suggest that the colorimetric wipes were able to detect both issues.

We met our second objective of validating the use of colorimetric wipes in a residential setting. Findings of a positive correlation between colorimetric response and ICP-OES laboratory analysis in the present study agree with similar trends in a comparison published from an occupational study. [13] We verified that detection sensitivity extended across various lead sources, including lead paint and occupational exposures. Furthermore, the colorimetric screening method demonstrated high specificity (87%) and overall moderate accuracy (78%) at the wipe's manufacturer-reported threshold of 18 µg/sample, as well as a commendably low rate of false negatives (13%, Table S2), supporting its utility as a reliable screening tool in identifying potential lead hazards in homes.

Despite its merits, the colorimetric wipe method has its limitations. One notable drawback lies in the inherently subjective nature of color readings, which can introduce variability and potential inaccuracies into the assessment process. Specifically, color can be a subjective descriptor, since an investigator could misread color under low or not full spectrum light, dirt-contaminated surfaces, surfaces with color interference metals, or if they are colorblind. We used the agreement of multiple investigators reading the wipes to minimize errors when reading the color. We tried to use the same investigators, when possible, to reduce biases in the readings. However, surface sampling inherently has a large variability, which is increased by adding the color step. The developing solutions spray patterns may not always cover the whole wipe, and the spray must cover the dust where the lead is present to be able to react and change color. Interferences with the color response are possible, as stated by the manufacturer [16]. Among elements detected in the wipes other than lead (see details in Fig. S1), chromium, copper, lead, and zinc had at least 50% of samples greater than the RL. Although it has been reported by the manufacturer that cadmium may cause color changes in the wipes that could mask the color response caused by lead [16], only 1% of the wipes had levels higher than the RL for cadmium, which suggested cadmium was likely not causing interference with the lead color reading. Unfortunately, we did not have information from the laboratory on other potential interferences beyond cadmium (i.e., silver, barium, titanium, and mercury) due to either these elements not being common from construction work or because of laboratory method limitations.

Moreover, the colorimetric reaction relies on using Rhodizonic acid potassium salt, which may cause irritation. Consequently, the colorimetric solution is added to the wipe after wiping the surface of interest. Trained investigators are advised to utilize protective equipment such as gloves and goggles to minimize the risk of adverse reactions during sample handling. Furthermore, although several organizations have promulgated standards for sampling lead and other metals on surfaces, uncertainty exists when determining an appropriate wipe sampling strategy and how to interpret sampling results. [13] Users must recognize that this method serves primarily as a rapid screening tool, suitable for initial assessments rather than comprehensive analyses. Color readings could aid in interpreting results, which would otherwise rely entirely on delayed and expensive quantitative analytical laboratory results if following existing home surface wipe guidelines.

Additional limitations of our study relate to sample collection and potential generalizability. Future studies using colorimetric wipes could include a more extensive data set with different tiers of exposure and potentially include before and after cleaning the contaminated surfaces. Although we collected 104 wipes for this study, we were able to only compare 81 samples with the laboratory results due to unexpected issues during the laboratory analysis. Another disadvantage in our comparison is that we prioritized the needs of each home when choosing sampling locations. Thus, there were no standard locations in the homes consistently sampled. Furthermore, since some surfaces were irregular (e.g., vehicle shift, vehicle door handle, worker boots), area measurements were only approximations in some cases, which is why we use units of µg/sample instead of µg/ft^2 unless compared to a guideline. Despite these challenges, we grouped categories of wipes for comparison to obtain statistical comparisons.

Despite limitations with colorimetric wipes, our study suggests that this method is valuable for screening purposes for homes with a potential occupational source of lead or lead from paint. In the realm of lead detection and mitigation, the commercially available and scientifically validated colorimetric wipe method proves to be both cost-effective and efficient. Colorimetric wipes cost approximately $2 to $10 per sample, far less than analytical laboratory testing, which can range from $60 to $160 per sample plus shipping. To make sampling more economical, as described in our procedures (Supplemental Materials Appendixes A, B), extra wipes can be purchased to supplement the colorimetric kits, as the solutions provided by the kit would allow sampling of as many samples as necessary during the sampling session. Beyond affordability, this method offers immediate feedback, which is advantageous in situations requiring prompt action. Its user-friendly design ensures ease of use, while the visual results, with red indicating concerning levels of lead, are easily understandable to non-experts. Even children in the homes were interested in the results of this technique and would clearly understand when a surface resulted in red that needed cleaning. The intensity of the color change on colorimetric wipes can instantly identify areas with the highest surface lead burden and aid in prioritizing work practice changes for intervention. Lastly, the method leaves no residue on surfaces, given that the colorimetric analysis is only performed after the sampling step is completed. The material wiping the surface is a laboratory-certified wet wipe, typically a Ghost Wipe (Environmental Express, Charleston, SC), which is wetted with 100% polyvinyl alcohol [35].

Recommendations

Potential limitations in this rapid screening tool's inherently subjective color reading can be ameliorated by collecting numerous colorimetric wipes and sending a sub-sample of wipes to the laboratory for confirmation. Future elemental analysis should include all potential elements that can cause color interference, which may require different analytical methods. To increase the use of colorimetric wipes in homes, it would be desirable that this technique be further evaluated to be added as an EPA-approved lead test kit [31]. Although the colorimetric wipes effectively identified lead hazards in paint (e.g., on window sills), the authors acknowledge that additional testing in a larger sample—particularly including homes without occupational lead exposure or lead-based paint—would be valuable in future research.

To increase a wider reception of the colorimetric wipes used in this study, manufacturers could tailor kits for residential use. Specifically, kits need 1 ft × 1 ft (0.3 m × 0.3 m) templates instead of the 10 cm × 10 cm templates typically used in workplaces, as larger areas are needed to be sampled in homes to collect enough dust, compared to workplaces that tend to be dustier. There is also a need to train practitioner audiences in the use of these wipes. Thus, to this end, the present study's authors created visual instructions on how to use the wipes (Supplemental Materials Appendix B) and are offering training demos using colorimetric wipes through continuing education courses to increase capacity in lead home investigations and reduce lead poisoning in children. As Ahmid et al. [22] suggested, increasing the use of colorimetric wipes as a citizen science tool would create opportunities for easily accessible public data, which could help track these issues on a larger scale to justify new policies and guidelines to address the lead problems nationwide. Lastly, although lead take-home has been a particular issue identified in the families of construction workers exposed to lead since the 90s [36], many other lead-exposed professions would also benefit from the use of these wipes to reduce lead exposure at home, such as lead battery recycling [37], electronics recycling [38], and shooting ranges [39], among others [40–42].

CONCLUSIONS

Colorimetric wipes were successfully used to assess lead levels on surfaces from homes and vehicles, particularly in cases where individuals worked in lead-exposed construction jobs and lived in older homes with potential lead paint issues. We determined that surface wipe color readings were well correlated with laboratory analysis results and with a low false negative rate, indicating that wipes may be a suitable tool for screening lead in home inspections with a potential occupational source. While wipes detect surface lead dust, XRF can identify the presence of lead in materials and objects—even when no visible dust is present. Thus, these screening methods are different but complementary and best when used together. However, the colorimetric wipes serve as a viable alternative screening tool to XRF, particularly in regions of the country lacking lead clinics or health departments equipped with traditional resources used to conduct lead home investigations such as XRF.

The recent lowering of the children's blood lead reference value to 3.5 µg/dL (from 5 µg/dL) [1, 43] has increased the number of cases tracked, and already overburdened public health departments might find colorimetric wipes a more economically viable and practical solution for performing home inspections to a larger number of homes. As a reference, a large, retrospective national study found that more than half of children under 6 years who have been tested for lead in their blood had detectable lead that was equal to or lower than 1 µg/dL, and 1.8% had levels of 5 µg/dL or more. [44] Performing surface wipe sampling following current EPA/HUD guidelines, along with the additional color analysis step used solely as a screening tool, would provide an ideal combination: immediate feedback on potential lead 'hot zones,' while still allowing the wipes to be sent to the laboratory for confirmation.

DATA AVAILABILITY

Surface sampling data are available upon request.

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AUTHOR CONTRIBUTIONS
DMC: Conceptualization, funding acquisition, project administration, data collection, methodology, validation, data analysis, recruitment, and wrote the original draft. YW: Data entry, validation, data analysis, data visualization, and wrote part of the original draft. MB: Data entry and validation. JIL: Methodology and administrative support. NAB: Recruitment. NTB: Chemical analysis. MPBM: Data collection, methodology, and graphics. JLP: Methodology, supervision, and data analysis expertise. All authors significantly reviewed, edited, and contributed to the final draft.

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COMPETING INTERESTS
The authors declare no competing interests.

ETHICS
The Boston University Medical Campus Institutional Review Board approved the study protocols before implementation. All participants provided written informed consent prior to enrollment in the study. All methods were performed in accordance with the relevant guidelines and regulations.

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