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Exposure profiles and source identifications for workers exposed to crystalline silica during a municipal waste incinerator relining period

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Abstract

In this study, respirable crystalline silica exposures to furnace relining workers of 7 exposure groups were assessed by conducting personal respirable dust samplings. All possible pollutant sources were identified for each exposure group through field observations, and bulk samples were randomly collected from each identified pollutant source. All collected samples were analyzed for their tridymite, cristobalite, and quartz contents by using the X-ray diffraction method. Results show that quartz was the only detectable crystalline silica content. We found that the resultant respirable quartz exposure levels presented in sequence for the 7 exposure groups (sand blasting > bottom ash cleaning > wall demolishing > relining > others > grid repairing > scaffold establishing) were different from that of the corresponding respirable dust exposure levels (bottom ash cleaning > wall demolishing > sand blasting > relining > grid repairing > scaffold establishing > others). 87.3–100% of workers' respirable quartz exposures of the 7 exposure groups exceeded the TLV-TWA (0.025 mg m^{-3}) indicating appropriate control strategies should be taken immediately. By comparing the fractions of quartz contained in personal respirable dust samples with that contained in all possible pollutant sources for each exposure group, this study identified main pollutant sources for each exposure group as: bottom ash cleaning and scaffold establishing: bottom ash; sand blasting: blasting sand; wall demolishing: refractory cement + wall ash; wall relining: refractory brick; grid repairing: wall ash + refractory cement; grid repairing: wall ash + refractory cement; others: blasting sand + bottom ash. Finally, effective control strategies were proposed for exposure reduction by using above information together with our field observations.

Keywords: Furnace relining; Crystalline silica; Exposure assessment; Main pollutant sources; Control strategy

1. Introduction

Workers in a variety of industries are being excessively exposed to respirable crystalline silica because of many materials containing it. The US National Institute for Occupational Safety and Health (NIOSH) indicates that more than 1.7 million US workers are potentially exposed to respirable crystalline silica [1]. In Taiwan, although the actual number of workers exposed to respirable crystalline silica remains unknown, the silicosis is rated the most prevalent occupational disease among all industries. With the exception for the mining industry, the refractory material manufacturing industry has the second largest number of workers with silicosis in all industries [2]. An epidemiological study conducted on 1022 male refractory brick workers employed for at least 6 months between 1954 and 1977 yielded a standard mortality ratio (SMR) of 1.51 (95% CI = 1.04–2.12) for respiratory tract cancers [3]. A study conducted in China on 6266 silicotic and nonsilicotic refractory brick workers employed before 1962 and followed for mortality from 1963 to 1985 found a standardized rate ratio (SRR) of 2.1 (no 95% CI was provided) for silicotic refractory brick workers [4]. Most importantly, crystalline

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silica has been confirmed as human carcinogen by IARC [5].

It is known that the refractory materials have been widely used in the metallurgical, foundry, and municipal waste incinerators for furnace lining purposes. Therefore, it is expected that furnace relining workers might be highly exposed to crystalline silica. But to the best of our knowledge only two case reports can be found in the literature. The first one was conducted on two metallurgical furnace relining workers, one mainly used a jackhammer for removing the old refractory lining material and the other conducted less jackhammering but focused more on collecting and dumping the pieces and chunks [6]. Results show that both workers' exposure levels were 1.23 and 2.52 times in magnitude of the US OSHA time-weighted average permissible exposure limit (PEL-TWA = 10 mg/m^3/(%crystalline silica + 2)) for respirable crystalline silica, respectively. The second study was conducted on one foundry worker while conducting the pneumatic chipping and mixing of the refractory materials for relining ladles [7]. Result shows that his respirable crystalline silica exposure level was ~2.74 times in magnitude of the US OSHA PEL-TWA. The above two case studies clearly indicate that furnace relining workers' respirable crystalline silica exposures could be very significant.

In Taiwan, the governmental labor statistics reveals that there are ~500 furnace relining workers currently being employed by 3 main contractors. Furnace relining workers can be divided into 7 exposure groups according to their work tasks. These include the bottom ash cleaning (for manually grabbing and tossing the bottom ash into a dumpster), scaffold establishing (for setting up the scaffold inside the furnace for the convenience of conducting following work tasks), sand blasting (for removing ash coated on the furnace wall by using the blasting sand and the cleaning of the fly ash from air pollution control devices), wall demolishing (by using a jackhammer for removing damaged refractory material), relining (including the mixing and patching the new refractory materials on the damaged furnace wall), grid repairing (for replacing or repairing the damaged furnace grids by welding), and others (for supervising the whole relining process). Although workers worked multiple projects concurrently, workers of the same exposure groups were specified to perform the same work tasks in different projects. On average all relining workers conducted furnace relining related work tasks for ~250 workdays per year as reported by the three contractors.

The first objective of this study was set out to assess exposure levels of furnace relining workers of different exposure groups of different work tasks. Considering workers of different exposure groups might be exposed to several pollutant sources simultaneously, the second objective of this study was to identify their main pollutant sources and to propose effective control strategies for exposure reductions for each exposure group.

2. Materials and methods

2.1. Sampling strategy and sample analysis

The whole study was conducted in a municipal waste incinerator during its annual furnace relining period. All workers in each exposure group were selected for conducting personal respirable dust samplings. A total of 58 workers were selected from the 7 selected exposure groups, including the bottom ash cleaning (n = 7), scaffold establishing (n = 6), sand blasting (n = 8), wall demolishing (n = 8), relining (n = 9), grid repairing (n = 13), and others (n = 7). This task-based approach has been used to assess workers' exposures for industries with dynamic occupational settings, such as constructions [8,9], geotechnical laboratory workers [10], slate industry [11], and quartz manufacturing [12]. The sampling train consisted of a high flow sampling pump (GilAir/Clock. Part No. 800508, Gillian Instrument Co., MA, USA), and a respirable dust cyclone (Part No. 456243, MAS Inc., PA, USA) followed by a 37-mm filter cassettes (Cat. No. 225-1. SKC Inc., PA, USA) with a PVC filter (Cat. No. P-503700, Omega Specialty Instrument Co., MA, USA). The sampling flow rate was set at ~1.7 L/min and was checked periodically throughout the entire sampling period (i.e., one work shift = ~8 h).

Table 1
Possible pollutant sources identified for the each of the seven selected exposure groups through the field observation of workers' designated work tasks and previous work tasks conducted by workers in the former exposure group

Exposure groups	Possible pollutant sources
Bottom ash cleaning	Bottom ash
Scaffold establishing	Bottom ash
Sand blasting	Blasting sand + wall ash + fly ash
Wall demolishing	Refractory cement + refractory brick + wall ash
Wall relining	Refractory cement + refractory brick
Grid repairing	Blasting sand + bottom ash + wall ash + fly ash + refractory cement + refractory brick
Others	Blasting sand + bottom ash + wall ash + fly ash + refractory cement + refractory brick

In this study, all possible pollutant sources for each selected exposure group were identified based on our field observation, particularly the observation of their designated work tasks and previous work tasks conducted by the former exposure group. Table 1 shows all possible pollutant sources for the 7 selected exposure groups. For each identified possible pollutant source, bulk samples were randomly collected from the field. A total of 24 samples were collected, including the bottom ash (n = 3), blasting sand (n = 3), wall ash (n = 9; including upper wall ash (n = 3), middle wall ash (n = 3), and lower wall ash (n = 3), refractory brick (n = 3), refractory cement (n = 3), and fly ash (n = 3).

In this study, all personal samples were analyzed for determining their respirable dust concentration per NIOSH Method 0600 [13]. Both personal samples and bulk samples were analyzed for their crystalline silica contents (including tridymite, cristobalite, and quartz) by using the X-ray diffraction per NIOSH Method 7500 [14]. This study yields method of detection limits (MDLs) of 0.020, 0.018, and 0.008 mg for tridymite, cristobalite, and quartz, respectively.

2.2. Data analysis

2.2.1. Characterizing exposure profiles

In this study, the method adopted to characterize the exposure profile was based on the method recommended by the American

Table 2
Respirable dust exposure profiles for the selected seven exposure groups

Exposure groups	Exposure profile				
	n	Log-normality	$AM_{(MVUE)}$ (mg/m^3)	95% confidence interval for $AM_{(MVUE)}$ (mg/m^3)	
				Lower	Upper
Bottom ash cleaning	8	Yes	9.21	5.56	14.2
Scaffold establishing	8	Yes	0.840	0.509	3.82
Sand blasting	7	Yes	1.84	0.967	8.07
Wall demolishing	8	Yes	2.72	0.886	9.23
Wall relining	10	Yes	1.21	0.848	2.30
Grid repairing	14	Yes	0.934	0.620	2.13
Others	8	Yes	0.726	0.386	3.06

Industrial Hygiene Association (AIHA) Exposure Assessment Strategies Committee [15]. Therefore, the log-normality, the average exposure level and its corresponding 95% confidence interval for each selected exposure group were calculated. The log-normality of the exposure profile for each exposure group was examined by using the *W*-test as suggested by Gilbert [16]. The arithmetic mean was used to describe the average exposure for a given exposure profile, since the value is directly related to its average and cumulative doses [17]. The minimum variance unbiased estimate (MVUE) method was used to estimate the arithmetic mean (AM_{MVUE}) and the resultant value was used to compare with the selected occupational exposure limit. This method is suitable for sample sizes from 5 to 500 with geometric standard deviations (GSDs) from 2 to 5. Detailed calculating procedures for both AM_{MVUE} and its 95% confidence interval have been described by Attfield and Hewett [18]. For each exposure profile, the point of estimate for the fraction of exposures exceeding the selected occupational exposure limit was calculated according to the method suggested by Hewett and Ganser [19].

2.2.2. Identification of main pollutant sources for each selected exposure group

In this study, the fractions of crystalline silica contained in all pollutant sources (by weight) were used to compare with that contained in personal respirable dust samples (by weight) to further determine the main pollutant sources for each exposure group to initiate effective control strategies for exposure reduction. Yet, it is true that the fraction of crystalline silica contained in the bulk samples of each possible pollutant source might not be exactly the same as that contained in the exposed respirable dusts, since we did not measure the respirable fraction of the collected bulk sample. But we assumed that the fraction of crystalline silica contained in the respirable dusts would be proportional to that contained in total dusts of each collected bulk sample. Based on this, we further assumed that the closer of the fraction of crystalline silica contained in a possible pollutant source to that contained in the exposed respirable dusts would had a greater contribution to the exposures of the given exposure group.

3. Results

3.1. Exposure profiles for workers exposed to respirable dusts

Table 2 shows exposure profiles of the respirable dust for the 7 selected exposure groups. We found that all resultant exposure profiles were log-normally distributed. The magnitude of the resultant respirable dust exposure levels for the 7 selected exposure groups in sequence were: (1) bottom ash cleaning 9.21 mg m^{-3}, (2) wall demolishing 2.72 mg m^{-3}, (3) sand blasting 1.84 mg m^{-3}, (4) wall relining 1.21 mg m^{-3}, (5) grid repairing 0.934 mg m^{-3}, (6) scaffold establishing 0.840 mg m^{-3}, and (7) others 0.726 mg m^{-3}, respectively. Among them, the top three were significantly higher than the rest four exposure groups. We also found that the exposure profiles of the respirable dust for the above 7 selected exposure groups

Table 3
Respirable quartz exposure profiles for the selected seven exposure groups

Exposure groups	Exposure profile				
	n	Log-normality	$AM_{(MVUE)}$ (mg/m^3)	95% confidence interval for $AM_{(MVUE)}$ (mg/m^3)	
				Lower	Upper
Bottom ash cleaning	8	Yes	0.386	0.248	0.553
Scaffold establishing	8	Yes	0.040	0.022	0.186
Sand blasting	7	Yes	0.578	0.306	2.58
Wall demolishing	8	Yes	0.116	0.032	0.412
Wall relining	10	Yes	0.041	0.030	0.825
Grid repairing	14	Yes	0.042	0.026	0.101
Others	8	Yes	0.082	0.051	0.386

Table 4
Fractions of workers' respirable quartz exposures exceeding the current TLV-TWA of 0.025 mg m^{-3} for the seven selected exposure groups

SEG	*n*	Fractions above TLV-TWA (%)
Bottom ash cleaning	8	100
Scaffold establishing	8	87.3
Sand blasting	7	100
Wall demolishing	8	97.8
Wall relining	10	88.6
Grid repairing	14	89.9
Others	8	96.7

Table 5
Fractions of quartz contained in respirable dusts (by weight) for samples collected from workers of the selected seven exposure groups

SEG	Fraction of quartz (%)		
	n	Mean	S.D.
Bottom ash cleaning	8	4.24	1.70
Scaffold establishing	8	4.83	1.87
Sand blasting	7	32.4	12.9
Wall demolishing	8	4.42	1.58
Wall relining	10	3.38	1.18
Grid repairing	14	4.55	1.94
Others	8	12.6	4.69

were consistently in the form of a log-normal distribution with GSDs ranging from 2.25 to 3.06.

3.2. Exposure profiles for workers exposed to crystalline silica

Table 3 shows respirable crystalline silica exposure profiles for the 7 selected exposure groups. We found that quartz was the only crystalline silica material containing in all collected samples. The magnitude of the resultant respirable quartz exposure levels in sequence for the 7 selected exposure groups were: (1) sand blasting 0.587 mg m^{-3}, (2) bottom ash cleaning 0.386 mg m^{-3}, (3) wall demolishing 0.116 mg m^{-3}, (4) others 0.082 mg m^{-3}, (5) grid repairing 0.042 mg m^{-3}, (6) wall relining 0.041 mg m^{-3}, and (7) scaffold establishing 0.040 mg m^{-3}, respectively. Among them, the top two were significantly higher than the rest four exposure groups. Again, we also found that the exposure profiles of the respirable quartz for the 7 selected exposure groups were all in the form of a log-normal distribution with GSDs ranging from 2.55 to 3.34. Table 4 shows that 87.3–100% respirable quartz exposures in all selected exposure groups exceeded the current time-weighted average threshold limit value (TLV-TWA = 0.025 mg m^{-3}) set by American Conference for Governmental Industrial Hygienists (ACGIH) [20]. The above results suggest that respirable quartz exposures of furnace relining workers were quite severe.

3.3. Crystalline silica contents in respirable dusts and possible pollutant sources

Table 5 shows the fractions of quartz contained in respirable dusts for the 7 selected exposure groups. Among them, both exposure groups of the sand blasting (32.4%) and others (12.6%) were significantly higher than the other selected exposure groups (scaffold establishing 4.83%; grid repairing 4.55%; wall demolition 4.42%; bottom cleaning 4.24%, and wall relining 3.38%). The above results suggest workers of different exposure groups were exposed to different pollutant sources.

On the other hand, we also found that quartz was the only detectable crystalline silica in all collected bulk samples. Table 6 shows the fractions of quartz contained in bulk samples collected from all possible pollutant sources. The fractions of the quartz contained in blasting sand (58.9%), bottom ash 11.1% and refractory brick (9.79%) were significantly higher than those contained in fly ash (6.98%), wall ash (5.76%) and refractory cement (3.09%). The above results suggest the existence of intrinsic differences among possible pollutant sources.

Table 6
Fractions of quartz contained in bulk samples (by weight) collected from all possible pollutant sources

Possible pollutant sources	Fraction of quartz (%)		
	n	Mean	S.D.
Bottom ash	3	11.1	0.711
Blasting sand	3	58.9	10.9
Wall ash (all)	9	5.76	1.98
Upper wall ash	3	6.69	1.17
Middle wall ash	3	6.34	0.851
Lower wall ash	3	4.24	1.09
Refractory brick	3	9.79	0.563
Refractory cement	3	3.09	0.151
Fly ash	3	6.98	0.810

4. Discussion

In Table 2 we found that the respirable dust exposure profiles for the 7 selected exposure groups were all log-normally distributed. The above results suggest that workers of each exposure group might have experienced to a very similar exposure scenario. The above inference can be confirmed through field observations (i.e., workers of each individual exposure group did conduct the same work tasks and were exposed to the same pollutant sources). For the same reason, it is not so surprising to see that the quartz exposure profiles for all selected exposure groups were also all log-normally distributed (Table 3).

Table 2 shows that workers of different exposure groups were exposed to respirable dust with different exposure levels. The top three exposure groups found in this study were: the bottom ash cleaning, wall demolishing, and sand blasting. By examining their involved work tasks, the highest exposure levels were clearly due to the involvement of agitation/disturbance of pollutant sources while conducting their work tasks. Although the agitation/disturbance of pollutant sources was also involved in the work tasks performed by wall relining workers (i.e., the dry mixing process), their lower exposure levels (in comparison with the above mentioned three exposure groups) could be due to the involvement of wet process during furnace relining material preparation. The lowest exposure levels were found in the exposure groups of the grid repairing, scaffold establishing and others. The lowest exposure levels found in both exposure groups of the grid repairing and scaffold establishing was not only because their work tasks (i.e., welding furnace grid and establishing scaffold) emitted very low dust concentrations, but also the generated airborne dusts from previous work tasks were removed from workplace atmosphere because of 1-day's sedimentation before their work tasks could be performed. On the other hand, the exposure group of the "others" were designated to supervise the whole relining process, and hence their lowest exposure levels might be because they worked less time (i.e., less than 3 h per day based on our field observations) inside the incinerator than other exposure groups.

In this study, we found that the quartz content was the only detectable crystalline silica contained in all collected samples (Table 3) warrants the need for further discussion. It is known that the polymorphs of free silica are temperature dependent and are reversible at atmospheric pressure. The transformation processes can be expressed as follows:

$$\text{Quartz} \Leftrightarrow \text{Tridymite} \Leftrightarrow \text{Cristobalite} \Leftrightarrow \text{Vitreoussilica}$$

Temperatures presented in sequence for the above phase transformations were 867, 1470, 1723 °C, respectively [21]. Considering the operating temperature specified for the studied incinerator was ∼1000 °C, the formation of tridymite content during the combustion process could be possible. But for safety concerns, it required a ∼3-day cooling period before the furnace relining process could be started. The above measurement might lead to the reversion of tridymite into quartz content during the cooling period, and hence resulted in the quartz content being the only detectable content in this study.

We found that the magnitude of the respirable quartz exposure levels in sequence for the 7 studied exposure groups (see Table 3) was quite different from that of the corresponding respirable dust exposure levels (see Table 2). This is mainly because worker crystalline silica exposure levels were not only affected by their respirable dust exposure levels, but also by the fractions of quartz contained in their exposed respirable dusts. The above inference can be confirmed by examining the fractions of quartz contained in the collected respirable dust (Table 5) and their corresponding respirable dust exposure levels (Table 2).

Table 4 shows the fractions of respirable quartz exposures that exceeded the current time-weighted average threshold limit value (TLV-TWA) for quartz as assigned by ACGIH (0.025 mg m^{-3}) for each individual exposure group [20]. The high fraction (range = 87.3–100%) clearly indicates that respirable quartz exposures for furnace relining workers were quite severe.

In Table 5 we found that the fractions of quartz contained in the respirable dusts existed intrinsic difference among all selected exposure groups. Indeed, in this study we did not measure the fractions of quartz contained in the respirable fraction of the collected bulk samples. But it can be expected that fraction in the respirable dusts would be proportional to that in total dusts of each collected bulk sample. Therefore, we further assumed that if the fraction of crystalline silica contained in a possible pollutant source was closer to the fraction of the exposed respirable dusts would had a greater contribution to the exposures of the given exposure group. Based on this, the comparison of the fractions of the quartz contained in the involved pollutant sources (see Table 6) with the fraction that contained in the exposed respirable dusts (see Table 5) would be able to help us to further prioritize the contributions of different pollutant sources for each exposure group.

Interestingly, it can be seen that the fractions of the quartz contained in the respirable dusts obtained from both exposure groups of the bottom ash cleaning and scaffold establishing (=4.24 and 4.83%, respectively, see Table 5) were lower than that in the only corresponding pollutant source (i.e., bottom ash = 11.1%, see Table 6). The above result might be because the specific weight of quartz was greater than combustion ash, and hence resulted in less quartz contained in airborne dusts than that in the bottom ash. For sand blasting workers, our field observations suggest that they were exposed to the blasting sand, wall ash, and fly ash simultaneously (Table 1). We also found that the fraction of quartz contained in their exposed respirable dusts (=32.4%, see Table 5) fell to the range of the above three pollutant sources (=58.9, 5.76, and 6.98%, respectively, see Table 6). Therefore, the high fraction of quartz found in the exposed respirable dusts suggests blasting sand, rather than the wall ash and fly ash, was the main contributor to their respirable quartz exposures. Similarly, we found that the fraction of quartz contained in the exposed respirable dusts for wall relining workers (=3.38%, see Table 5) also fell to the range of their possible pollutant sources (i.e., refractory brick and refractory cement = 3.09 and 9.79%, respectively, see Table 6). Therefore, it could be expected that they were mainly exposed to the refractory brick, rather than the refractory cement. For the same reason, the fraction of quartz contained in the exposed respirable dusts for wall demolishing workers (=4.42%, see Table 5) suggests that both refractory cement and wall ash (=3.09 and 5.76%, respectively, see Table 6) might play more important role than the refractory brick (=9.79%, see Table 6) on their respirable quartz exposures. Finally, because both the grid repairing and "other" groups were exposed to all possible pollutant sources, and hence the fractions of quartz contained in their exposed respirable dusts (=4.55 and 12.6%, respectively, see Table 5) fell to the range 3.09–58.9% of all pollution sources (see Table 6). The low fraction of quartz contained in the exposed respirable dusts for grid repairing workers (=4.55%, see Table 5) suggests that their exposures were mainly contributed by aerosols generated during the furnace demolition period (i.e., the wall ash and destroyed refractory cement = 5.76 and 3.09%, respectively; see Table 6). On the other hand, the high fraction found for "others" (=12.6%; see Table 5) suggesting that they could be mainly exposed to blasting sand (=58.9%) during the sand blasting process and bottom ash (=11.1%; see Table 6) during the bottom ash cleaning process.

Here, it should be noted that even different exposure groups were mainly exposed to the same pollutant sources, different control strategies might be needed simply because their exposures might be resultant from different causes. By taking both bottom ash cleaning and scaffold establishing workers as an example, although both were mainly exposed to the bottom ash, the respirable quartz exposures to former were directly related

Table 7
Summary of main pollutant sources and their control strategies for each of the selected seven exposure groups based on our field observation

Exposure groups	Main pollutant sources	Control strategies
Bottom ash cleaning	Bottom ash	1. Wet process 2. PPE[a]
Scaffold establishing	Bottom ash	1. Wet process during the bottom ash cleaning period 2. Stronger forced ventilation 3. PPE[a]
Sand blasting	Blasting sand	1. Changing blasting sand with shots 2. PPE
Wall demolishing	Refractory cement, wall ash	1. PPE[a]
Wall relining	Refractory brick	1. PPE[a]
Grid repairing	Wall ash, refractory cement	1. Stronger forced ventilation 2. PPE[a]
Others	Blasting sand, bottom ash	1. Changing blasting sand with shots during the sand blasting period 2. Wet process during bottom ash cleaning period 3. Stronger forced ventilation during the scaffold establishing period 4. PPE[a]

[a] Personal protective equipment.

to their work tasks (i.e., cleaning the bottom ash). On the other hand, the latter were related to residual bottom ash existed in the air arising from previous work tasks. Therefore, if the wet process could be adopted in the bottom ash cleaning period, then the measurement would be beneficial to both exposure groups. On the other hand, if personal protective equipment (PPE) was adopted for exposure abatement strategy for the former, then either PPE or stronger forced ventilation could be adopted for the latter. Table 7 summarizes main pollutant sources and proposed control strategies for each of the seven studied exposure group based on our field observation. It is concluded that the source identification technique used in this study can not only help the industry to prioritize the main pollutant sources for each exposure group, but also can provide useful information for initiating effective control strategies.

5. Conclusions

In this study, we found that workers in each selected exposure group did share a very similar exposure scenario, and hence their respirable dust and respirable quartz exposure levels can be characterized by using a log-normal distribution. Workers of different exposure groups exposed to respirable dusts with different exposure levels could be explained by the intrinsic difference in their involved work tasks. But the differences in their respirable quartz exposure levels were not only resulting from the differences in their respirable dust exposure levels, but also the fractions of quartz contained in their exposed respirable dusts. High fractions of workers' respirable quartz exposures exceeding the current limit value clearly suggest the importance to initiate effective control strategies for all furnace relining workers. By comparing the fractions of quartz contained in the respirable dusts with that contained in all possible pollutant sources could not only help the industry to prioritize possible pollutant sources for each exposure group but also could be beneficial for them to initiate effective control strategies.

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