Quantitative assessment of occupational exposure to total indium dust in Japanese indium plants

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Abstract: This study quantitatively assessed personal exposure of 86 workers to indium compounds as total dust at 11 Japanese indium plants. The personal exposures to indium concentrations in the breathing zone during an 8 h work-shift were determined by ICP-MS. The arithmetic mean indium concentration of all the workers was 0.098 mg Indium (In)/m^3, with individual values ranging from 0.0001 to 1.421 mg In/m^3. There were 11 workers whose exposure to indium concentrations exceeded the American Conference of Governmental Industrial Hygienists’ Threshold Limit Value-Time Weighted Average (TLV-TWA) of 0.1 mg In/m^3. Based on the condition TLV-TWA<X95 (upper 95th percentile of log-normal distribution), five indium plants were judged as “control measures required”, while 3 other plants were evaluated as “control measures not required”. Five workers belonging to the worst group were exposed to far higher indium concentrations than the TLV-TWA. Another group of 5 workers belonging to the best group was exposed to far lower indium concentrations than the TLV-TWA, and this was attributed to the stringent engineering control measures used at their workplaces. The quantitative assessment of occupational exposure to indium dust was influenced by different occupational exposure limit values without carcinogenicity and particle size-selectivity of indium particulates or “total” dust.

Key words: Indium dust, Total dust, Indium-Tin-Oxide, Personal sampling, Particle size-selectivity, Upper 95th percentile

Introduction

Exposure of workers to hardly soluble indium dust was reported to have caused 7 cases of interstitial pneumonia in Japan, 2 cases of pulmonary alveolar proteinosis (PAP) in the USA, and 1 case of PAP in China1). It is of prime importance to protect workers from health outcomes due to excessive exposure to indium dust with reference to the occupational exposure limit (OEL). Different OEL values for indium dust have been recommended by several international organizations of occupational health. The Threshold Limit Value-Time Weighted Average (TLV-TWA) of 0.1 mg/m^3 of indium for indium and indium compounds was recommended by the American Conference of Governmental Industrial Hygienists (ACGIH)2). The same value of 0.1 mg indium (In)/m^3 was designated as the Recommended Exposure Limit (REL) for indium compounds by the National Institute for Occupational Safety and Health (NIOSH)3). The Japanese Ministry of Health, Labour and Welfare (MHLW) has issued the

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Technical Guideline for Preventing Health Impairment of Workers Engaged in the Indium Tin Oxide (ITO) Handling Processes, which defines two occupational standards: an Acceptable Exposure Concentration Limit of $3 \times 10^{-4}$ mg In/m$^3$, and a Target Concentration of 0.01 mg In/m$^3$ in the respirable fraction of indium dust. The Technical Guideline designates the particle size-selective capturing of indium particles of cut-size 4 µm (50% efficiency) as respirable dust, which is hazardous when deposited in the deep gas-exchange region of the lungs. On the other hand, ACGIH’s TLV and NIOSH’s REL for indium dust are expressed in terms of total dust, since indium dust is not designated an “inhalable, thoracic or respirable fraction of particulate matter depending on particle size-selective sampling criteria”, but as “particulates not otherwise regulated, total”.

Our previous study, a generic control banding assessment of workers’ health risks in 13 Japanese indium plants using the COSHH Essentials, noted that since indium dust is highly hazardous to workers’ health, the majority of indium-handling operations in the 13 plants were subject to “Control Approaches 3 and 4 according to the COSHH Essentials”, and that highly efficient engineering control measures such as enclosed-type local exhaust ventilation (LEV) and respiratory protective equipment (RPE) with high Assigned Protection Factor (APF) should be provided. However, there were some limitations regarding the generic control banding assessment, since the hazard levels, the amount in daily use and the “dustiness” characteristics of indium dust in the workplace were broadly categorized using simple scales. The present study was designed to quantitatively assess the personal exposures of 86 indium-handling workers to indium compounds in terms of total dust at 11 Japanese indium plants with reference to the TLV-TWA. We also examined the industrial hygiene control measures used in the 11 plants for an efficiency evaluation in comparison to the OEL using the statistical exposure indices of the exposure concentrations obtained.

Materials and Methods

Subjects of study

Thirteen plants enlisted for the preliminary investigation were chosen from among the 38 companies in Japan whose annual production of indium exceeded 500 kg in 2009. Since the generic control banding assessment of occupational exposure to indium and its compounds in the 13 indium plants has been carried out in a previous study, 11 out of the 13 indium plants were investigated for the comprehensive assessment of personal exposure of workers to indium dust in the present study. These 11 companies consisted of 3 plants having 300 employees or more, 4 plants having 100 to 299 employees, 1 plant having 50 to 99 employees and 3 plants having less than 50 employees. We examined the personal exposures of 86 workers to indium compounds in terms of total dust, as a sample of the 279 workers assigned to various indium-handling operations in the 11 plants.

Analysis of indium

The analysis of indium was carried out with a slight modification to the method described in the MLHW’s Technical Guideline and the NIOSH Manual of Analytical Methods No.7301 for indium, using an Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) (Agilent7500i, Agilent Technology, Japan). The analytical conditions of ICP-MS are summarized as follows: 1,400 Watts of RF power at 1.7 V, flow rates of 15 l/min for the plasma gas and 1.0 l/min for the carrier gas, and measured m/z values of 115 and 118. The membrane filter on which indium-containing particulate matter was collected was placed into a flask containing 30 ml of mixed acid (nitric acid (Wako Pure Chemicals, Ltd.), ultra-pure water (18 MΩcm, Toraypure LV-10T, Japan) and hydrochloric acid (Wako Pure Chemicals, Ltd.), ultra-pure water (18 MΩcm, Toraypure LV-10T, Japan)) in the ratio of 1:3:4 and subjected to ultrasonic agitation for 60 min, before being digested on a hot plate at 160°C for 60 min. A standard solution of indium for atomic absorption spectrometric analysis (Kanto Chemicals, Japan) was used in the preparation of the calibration curve for the quantitation. The calibration curve of peak counts of m/z (Y) in ICP-MS versus indium concentrations (X) in the mixed acid (ng/ml) used in the present study was found to be highly linear in the range of 0.5 mg/ml to 100 ng/ml and highly correlated; the regression equation was $Y=2270X + 15310$ with a correlation coefficient of 0.9997. The quantitation limit of indium was found to be 0.07 mg/ml. The quantitation limit of airborne indium was estimated to be 0.003 µg/m$^3$, based on assumptions of the final volume of the solution used in the analysis being 40 ml per filter, and the volume of collected workplace air being 960 l at a flow rate of 2 l/min.

Determination of personal exposure concentrations of indium

Indium compounds in the total dust suspended in the workplace air collected in the workers’ breathing zones were analyzed for personal exposure concentrations of...
indium which were expressed as the 8-h time-weighted average (8h-TWA). The total dust containing indium compounds was collected on a mixed cellulose ester membrane filter (0.8-µm pore size, 37-mm diameter, Japan Millipore, Co.) in a cassette filter holder (SKC, Inc.). The workplace air was drawn at a flow rate of 1.0 l/min for a sampling period of 6 h or longer, except during lunchtime, using a portable suction pump (Aircheck 2000, SKC, Inc.). We used the NIOSH sampling method (NMAM0500) for the collection of indium dust as “particulates not otherwise regulated, total”. The sampling period for the collection of total dust was also in accordance with the directions of the NIOSH Occupational Exposure Sampling Strategy Manual that the measurement results are valid only for 6 out of 8 h, or the sampling portion of the period should cover at least 70% to 80% of the full exposure period. The indium concentration of personal exposure to total indium dust expressed as 8h-TWA was calculated using the following equation:

\[
8h\text{-TWA} = \frac{(C_{pi} \times T_{pi})}{8 \text{ h}},
\]

where \(C_{pi}\) (mg/m\(^3\)) and \(T_{pi}\) (h) indicate observed indium concentration of exposure to the total dust during the sampling period, and the period of time used for sampling the indium dust, respectively.

**Results**

**Indium-exposed workers examined**

Table 1 presents the basic demographic data of the 86 indium-exposed workers employed in various indium-handling operations at the 11 indium plants. The indium plants were grouped into the two different sectors of the indium industry: 4 plants performing recycling/reclamation, and 7 plants manufacturing electronic devices. Various forms of indium materials such as metallic indium, ITO, indium oxide, indium hydroxide and indium phosphide are handled in these operations. The indium-handling processes characterized by weighing, bagging, crushing, casting and sintering were found to be dusty, while other processes, dehydration and electrophoresis, were deemed to be clean. Grinding and cutting of indium crystals were performed within either a glove box or an enclosed-type LEV to prevent excessive exposure to indium materials.

In Fig. 1, individual 8h-TWA indium concentrations of the 86 workers are plotted on a logarithmic scale. The individual workers are labelled with numbers and uncapsitalized letters, a−k, which represent each of the 11 indium plants. The logarithmic concentrations of personal exposure to indium compounds in the total dust were found to follow a sigmoidal curve, indicating a log-normal distribution.

Table 2 shows the indium concentrations in total dust as determined by the personal exposures of the workers in the breathing zone at the 11 indium plants. The AM indium concentration of the 86 workers was 0.098 mg In/m\(^3\), with individual values ranging from 0.0001 mg In/m\(^3\) to 1.421 mg In/m\(^3\). The exposure concentrations could be regarded as following the log-normal distributions according to the Kolmogorov-Smirnov test (Excel-Toukei, Social Survey Research Information Co., Ltd.). We used two different methods for defining and judging exposure profiles to determine the acceptability of occupational exposure to total indium dust. First, we compared the personal exposure data of individual workers with ACGIH’s TLV-TWA as the OEL, and AL as one-half of NIOSH’s REL. There were 11 (13%) workers whose exposures to indium concentrations exceeded the TLV-TWA. Seven workers were from 3 recycling/reclamation plants, and four workers were from 3 plants manufacturing electronic devices. Nineteen (22%) of the 86 indium-exposed workers had indium concentrations exceeding the AL. We also used the condition TLV<X\(_{95}\) to determine unacceptable exposures which required control measures in the workplace. Five indium plants (a, d, e, g, and i) were evaluated as requiring
control measures. Three plants (f, h, and j) were evaluated as not requiring control measures. The remaining 3 plants (b, c, and k) which employed less than 50 workers were evaluated as requiring control measures using the conditions of $AL<Max$ for Plant b, and $TLV<AM$ for Plants c and k.

The worst and best personal exposures to indium dust

Table 3 presents the worst and best the 86 of 5 cases of indium concentrations from among the personal exposures of workers employed in various indium-handling operations at the 11 plants. In the worst group of 5 cases, all the workers were exposed to almost 10-fold higher indium concentrations than the TLV-TWA. They wore reusable half-face masks with particle filters with an assigned protection factor (APF) of 10. However, the engineering control measures of LEV were inadequate.

Table 3 also shows that all 5 workers of the best 5 cases were exposed to far lower indium concentrations than the TLV-TWA. Three workers wore no masks, or disposable, unwoven mask in the dusty operation of grinding and cutting InP crystals. However, at their workplaces a glove box or enclosed type LEV was installed and this type of installation can further reduce the exposure concentration to 1/10 of that of a hood type LEV7). The other two workers were employed in an indium residue-handling operation and they wore half-face dust masks without any LEV in the workplace.

Discussion

The present results indicate that 11 out of 86 indium-exposed workers were exposed to higher indium concentrations than the TLV-TWA. There were also 19 (22%)
Table 1. Summary of 11 Japanese indium plants examined for indium material handled, operations in manufacturing processes, number of employees and number of workers exposed to indium compounds in total dust

| Plants | Sectors of indium industry | Number of employees | Indium compounds handled | Operations in indium-manufacturing processes | Number of examined workers exposed to indium/Total number of possibly exposed workers |
|--------|---------------------------|---------------------|-------------------------|-----------------------------------------------|--------------------------------------------------------------------------------|
| a      | Recycling/Reclamation     | 21                  | ITO, Metallic indium, Indium hydroxide | Crushing raw materials, Filling and bagging, Solubilizing indium materials | 8/14                                                                         |
| b      | Manufacturing electronic devices including ITO | 118                | Indium hydroxide, ITO | Ingot filling, Solubilizing, Drying and crushing | 3/18                                                                       |
| c      | Manufacturing electronic devices including ITO | 135                | ITO                      | Pellet and powder filling, Crushing             | 1/2                                                                         |
| d      | Manufacturing electronic devices including transparent electrodes and panels | 486                | Indium hydroxide, ITO | Weighing and powder filling, Formulation, Bonding, Grinding and cleaning | 12/33                                                                       |
| e      | Manufacturing electronic devices including transparent electrodes and panels | 150                | Indium hydroxide, ITO | Deposition by beam evaporation, Filling into a 1.8-l container, Maintenance (powder) | 9/14                                                                       |
| f      | Manufacturing electronic devices including sputtering target | 70                 | ITO                      | Shot-blasting, Dust cleaning                    | 6/10                                                                       |
| g      | Recycling/Reclamation     | 579                 | Indium oxide, Indium hydroxide | Filtering and drying, Crushing, Powder filling | 11/32                                                                      |
| h      | Manufacturing electronic devices including sputtering target | 192                | ITO                      | Sintering (Ingot, solubilized metal), Crushing and bonding (clumped metal), Grinding and Powder filling | 9/14                                                                       |
| i      | Manufacturing electronic devices including sputtering target, Surface materials and semiconductors | 318                | Metallic indium, ITO, Indium hydroxide, Indium phosphide | Pressing (cake-like), Bonding (clumped metal), Drying, Filling, Grinding and dust cleaning | 17/114                                                                      |
| j      | Recycling/Reclamation     | 45                  | Metallic indium, ITO | Ingot melting and solubilizing, Electrophoresis, Sintering | 8/11                                                                       |
| k      | Recycling/Reclamation     | 25                  | Metallic indium, ITO | Crushing, Solubilizing, Sintering ingot         | 2/3                                                                         |

workers out of the 86 whose indium concentrations exceeded the AL, suggesting that certain provisions must be initiated at their workplaces, such as consecutive exposure measurements, training of employees, and medical surveillance, according to the NIOSH Occupational Exposure Sampling Strategy Manual. It has been reported that the condition TLV<sub>X95</sub> can be used as a definition of “control measures required.” By this definition, eight of the eleven indium plants required control measures, while the other 3 plants were evaluated as not requiring control measures. Notably, all 5 workers of the worst exposure group were employed in various indium-handling operations, such as collection of indium oxide dust, crushing and sintering and cutting of ITO targets, were exposed to much higher indium concentrations of total dust than the TLV-TWA. The present results are consistent with the findings of Cummings et al. in a NIOSH survey of personal breathing zone analysis of indium total dust concentrations in US companies. They reported that various activities with increased potential for indium exposure included the manufacturing of inorganic indium compounds, ITO sputter target resurfacing, and abrasive blasting to remove residues. They also reported the pneumatic sanding of ITO targets resulted in high worker exposure to indium of 3.1 mg In/m<sup>3</sup> of total dust. The present results are consistent with the findings of Miyauchi et al. that breathing zone indium concentrations of total dust are higher in the processes of ITO milling (0.67 mg In/m<sup>3</sup> as TWA), and pulverization and heating (7.1 mg In/m<sup>3</sup> as TWA) than in the electrolyte refining process (0.043 mg In/m<sup>3</sup> as TWA).
Table 2. Indium concentrations (mg In/m$^3$) as determined by personal exposure to total dust of indium at the breathing zone with reference to ACGIH’s TLV-TWA

| Items                        | Plants | Number of workers whose exposure concentrations exceeded the TLV-TWA (0.1 mg In/m$^3$) | Number of workers whose exposure concentrations exceeded the AL (0.05 mg In/m$^3$) | Min (mg In/m$^3$) | Max (mg In/m$^3$) | AM (mg In/m$^3$) | GM (mg In/m$^3$) | GSD | X$_{95}$ (mg In/m$^3$) | Statistical significance of log-normal distribution at $p \geq 0.10$ by the Kolmogorov-Smirnov test |
|------------------------------|--------|----------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-------------------|-------------------|-----------------|-----------------|-----|----------------------|-----------------------------------------------|
| Indium concentrations in total dust | a      | 8                                                                               | 3                                                                            | 0.004             | 0.760             | 0.146           | 0.052           | 4.864 | 0.701                | *$p_{\leq 0.10}$                               |
|                               | b      | 3                                                                               | 0                                                                            | 0.011             | 0.085             | 0.044           | NC              | NC              | NC                   | NC                                            |
|                               | c      | 1                                                                               | 1                                                                            | 0.120             | 0.120             | 0.120           | NC              | NC              | NC                   | NC                                            |
|                               | d      | 12                                                                              | 1                                                                            | 0.002             | 0.194             | 0.033           | 0.013           | 4.137 | 0.131                | *$p_{\leq 0.10}$                               |
|                               | e      | 9                                                                               | 3                                                                            | 0.001             | 1.421             | 0.345           | 0.073           | 9.693 | 3.047                | $p_{=0.0924}$                                 |
|                               | f      | 6                                                                               | 0                                                                            | 0.0001            | 0.001             | 0.000           | 0.0003          | 2.321 | 0.001                | *$p_{\leq 0.10}$                               |
|                               | g      | 11                                                                              | 1                                                                            | 0.006             | 0.469             | 0.069           | 0.028           | 3.403 | 0.209                | *$p_{\leq 0.10}$                               |
|                               | h      | 9                                                                               | 0                                                                            | 0.002             | 0.090             | 0.020           | 0.012           | 2.894 | 0.067                | *$p_{\leq 0.10}$                               |
|                               | i      | 17                                                                              | 1                                                                            | 0.0004            | 0.965             | 0.071           | 0.010           | 6.668 | 0.220                | *$p_{\leq 0.10}$                               |
|                               | j      | 8                                                                               | 0                                                                            | 0.001             | 0.026             | 0.009           | 0.005           | 3.497 | 0.035                | *$p_{\leq 0.10}$                               |
|                               | k      | 2                                                                               | 1                                                                            | 0.002             | 1.273             | 0.638           | NC              | NC              | NC                   | NC                                            |
| Total                        |        | 86                                                                              | 11                                                                           | 0.0001            | 1.421             | 0.098           | 0.014           | 7.610 | 0.393                | *$p_{\leq 0.10}$                               |

AL: Action level; Min: Minimum value; Max: Maximum value; AM: Arithmetic mean; GM: Geometric mean; GSD: Geometric standard deviation; X$_{95}$: Upper 95th percentile of a log-normal distribution; NC: Not calculated.

Table 3. The worst and best 5 cases of personal exposure to indium compounds in total dust in the breathing zone, and industrial hygiene control measures being used at their workplaces

| Worst group of 5 cases | Personal exposure concentrations of indium in total dust | Indium-handling operations (Time spent at the workplace) | Indium exposure concentration as 8h-TWA (mg In/m$^3$) | Local Exhaust Ventilation (LEV) | Respiratory Protective Equipment (RPE) |
|------------------------|--------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------|---------------------------------|--------------------------------------|
| Worker e8              | Collection of indium oxide dust into 18-l container (44 min) | 1.421                                                  | None                                             | Half-face dust mask              |
| Worker k2              | Crushing (5 min), Sintering (25 min)                    | 1.273                                                  | Hood-type LEV                                    | Half-face dust mask              |
| Worker e9              | Collection of indium oxide powder into a 18-l container (44 min) | 1.256                                                  | None                                             | Half-face dust mask              |
| Worker i17             | Cutting off and crushing of ITO target (30 min)         | 0.965                                                  | Hood-type LEV                                    | Half-face dust mask              |
| Worker a6              | Weighing and bagging (120 min)                         | 0.760                                                  | Hood-type LEV                                    | Half-face dust mask              |
| Best group             | Worker f6                                              | Recovery of indium residue in the ditch (16 min)       | 0.0001                                           | None                            | Half-face dust mask               |
|                        | Worker f5                                              | Recovery and transfer of indium residue from the ditch (13 min) | 0.0002                                           | None                            | Half-face dust mask               |
|                        | Worker f3                                              | Shot-blasting (380 min)                                | 0.0003                                           | Enclosed-type LEV                | Half-face dust mask               |
|                        | Worker i9                                              | Grinding and cutting off of InP crystal (360 min)      | 0.0004                                           | Glove box                       | Disposable, unwoven mask          |
|                        | Worker i8                                              | Grinding and cutting off of InP single crystal (360 min) | 0.0005                                           | Enclosed-type LEV                | None                               |
in an indium-recycling/reclamation plant.

Two workers, e8 and e9, were exposed to very high indium concentrations of 1.421 mg In/m³ and 1.256 mg In/m³, respectively. These values were 14- and 13-fold higher than the TLV-TWA. Those 2 workers wore half-face dust masks with an APF of 10 and no LEV system was installed at their workplaces. We recommended the employer to implement two kinds of control measures: provide dust masks with an APF of 25 in accordance with the NIOSH Respirator Selection Logic14), and install a hood-type LEV at their workplaces, since the exposure concentration can be reduced to 1/10 of that of general ventilation by this kind of LEV7).

Three workers, k2, i17, and a6, were exposed to higher indium dust concentrations than the TLV-TWA. Their control measures were found to be inadequate. They wore half-face masks with an APF of 10 and were employed in indium-handling operations at workplaces having only a hood-type LEV. Since the measured capture velocities were found to fall to approximately 0.1 m/sec, and the canopy hood was positioned distant from the contaminant source of the crushing operation, engineering control measures of increasing the capture velocity of the LEV and replacing the LEV with an enclosed-type LEV near the contaminant source were recommended. Effective mitigation of the exposure concentration to below the TLV-TWA was thought to be achievable through the wearing of full-face dust masks with a higher APF in accordance with the NIOSH Respirator Selection Logic14).

It was noteworthy that 3 workers, f3, i8, and i9, were exposed to indium concentrations of total dust far below the TLV-TWA, even though 2 of the 3 workers wore no dust mask, or disposable, unwoven masks. The effective mitigation was attributed to more stringent engineering control measures, such as the installation of a glove box and an enclosed-type LEV, both of which have been reported to reduce the exposure concentrations to 1/10 of that of a hood-type LEV7).

Two clear differences can be recognized between ACGIH’s TLV-TWA or NIOSH’s REL-TWA and the Technical Guideline’s occupational standards. ACGIH2, 15) recommends a TLV-TWA of 0.1 mg In/m³ of total dust on the basis of adverse skeletal and gastrointestinal effects and pulmonary toxicity associated with inhaled indium without notations of carcinogenicity. NIOSH recommends a REL-TWA of 0.1 mg In/m³ total dust for indium compounds without designation of occupational carcinogenicity7). On the other hand, the Technical Guideline’s occupational standard4) “Acceptable Exposure Concentration Limit” of 3 × 10⁻⁴ mg In/m³ respirable dust was derived from an empirical dose-response relationship between the inhalation exposure concentrations of respirable ITO dust and incidences of bronchio-alveolar cancer in a 2-yr inhalation carcinogenicity study of rats16). Our previous control banding study5) revealed that the OEL value for indium dust in indium plants should be maintained below 0.01 mg In/m³, since airborne indium dust was highly hazardous with “high dustiness”. Cummings et al.12) suggested that particulate matter containing indium compounds with a mass median aerodynamic diameter less than 4 µm can penetrate into the deep alveolar region when inhaled, and that this would be toxicologically relevant for chronic respiratory diseases and lung cancer. Further study will be needed to quantitatively assess exposures to airborne indium dust with reference to a particle size-selective OEL value expressed in inhalable, thoracic and respirable fractions of particulate matter, in addition to the quantitative risk assessment of indium dust for human carcinogenicity.

Conclusion

The personal exposures of 86 workers to indium and indium compounds in total dust at 11 Japanese indium plants whose annual production exceeded 500 kg, was determined as time-weighted averages by ICP-MS. There were 11 workers whose indium concentrations of personal exposure to total dust exceeded the TLV-TWA. Based on the condition TLV<X₉₅, five indium plants judged to require control measures for their indium-handling operations. Several workers of the worst exposure group were exposed to much higher concentrations of indium dust than the TLV-TWA. The control measures of LEV and RPE were found to be inadequate at their workplaces. Another group of 5 workers was exposed to indium concentrations of total dust that were much lower than the TLV-TWA, and this was attributed to the stringent engineering control measures adopted at their workplaces.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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References

1) Omae K, Nakano M, Tanaka A, Hirata M, Hamaguchi T, Chonan T (2011) Indium lung—case reports and epidemiology. Int Arch Occup Environ Health 84, 471–7. [Medline] [CrossRef]

2) American Conference of Governmental Industrial Hygiene (ACGIH) (2016) 2016 Threshold Limit Values for Chemical Substances in the work environment. Cincinnati.

3) The National Institute for Occupational Safety and Health (NIOSH) NIOSH Pocket Guide to Chemical Hazards. Indium Compounds. NIOSH, Cincinnati. https://www.cdc.gov/niosh/npg/npgd0341.html. Accessed March 5, 2018.

4) Japan Ministry of Labour, Health and Welfare (MLHW) (2010) The technical Guideline for Preventing Health Impairment of Workers Engaged in the Indium Tin Oxide Handling Processes, issued on December 22, 2010 as the Notification of Labour Standards Bureau No.1222-3 by MLHW, Bureau of Labour Standards, Division of Industrial Safety and Health.

5) National Institute for Occupational Health (NIOSH) NIOSH Manual for Analytical Methods No.0500 Issue 2 (15 August 1994) Particulates not otherwise regulated, total. https://www.cdc.gov/niosh/docs/2003-154/pdfs/7301.pdf. Accessed May 1, 2018.

6) Higashikubo I, Arito H, Ando K, Araki A, Shimizu H, Sakurai H (2018) Control banding assessment of workers’ exposure to indium and its compounds in 13 Japanese indium plants. J Occup Health 60, 263–70. [Medline] [CrossRef]

7) Health and Safety Executive (HSE) UK. The Control of Substances Hazardous to Health (COSHH) Essentials: Controlling Exposure to Chemicals. A Simple Control Banding Approach. http://www.hse.gov.uk/pubns/guidance/coshh-technical-basis.pdf. Accessed March 29, 2018.

8) National Institute for Occupational Health (NIOSH) (2003) NIOSH Manual for Analytical Methods No.7301 (15 March 2003) for Indium. https://www.cdc.gov/niosh/docs/2003-154/pdfs/7301.pdf. Accessed March 5, 2018.

9) National Institute for Occupational Safety and Health (NIOSH) (1977) Occupational Exposure Sampling Strategy Manual. DHEW (NIOSH) Publication No. 77-173. January 1977. US. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, NIOSH, Cincinnati.

10) Bullock WH, Ignacio JS (2006) A Strategy for Assessing and Managing Occupational Exposures, 3rd Ed. American Industrial Hygiene Association, Fairfax.

11) Hashimoto H, Yamada K, Hori H, Kumagai S, Murata M, Nagoya T, Nakahara H, Mochida N (2015) Guideline for personal exposure monitoring of chemicals. Sangyo Eiseigaku Zasshi (Formerly Sangyo Igaku, Jpn J Ind Health) 57, A13 – 60 (In Japanese).

12) Cummings KJ, Virji MA, Park JY, Stanton ML, Edwards NT, Trappnell BC, Carey B, Stefaniak AB, Kreiss K (2016) Respirable indium exposures, plasma indium, and respiratory health among indium-tin oxide (ITO) workers. Am J Ind Med 59, 522–31. [Medline] [CrossRef]

13) Miyauchi H, Minozoe A, Tanaka S, Tanaka A, Hirata M, Nakaza M, Arito H, Eitaki Y, Nakano M, Omae K (2012) Assessment of workplace air concentrations of indium dust in an indium-recycling plant. J Occup Health 54, 103–11. [Medline] [CrossRef]

14) National Institute for Occupational Safety and Health (NIOSH) (2004) NIOSH Respirator Selection Logic. DHHS (NIOSH) Publication No.2005-100. NIOSH, Cincinnati.

15) American Conference of Governmental Industrial Hygienists (ACGIH) (2001) Indium and Compounds. In: Documentation of the Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs). [CD-ROM 2001], ACGIH, Cincinnati.

16) Nagano K, Nishizawa T, Umeda Y, Kasai T, Noguchi T, Gotoh K, Ikawa N, Eitaki Y, Kawasaki Y, Yamauchi T, Arito H, Fukushima S (2011) Inhalation carcinogenicity and chronic toxicity of indium-tin oxide in rats and mice. J Occup Health 53, 175–87. [Medline] [CrossRef]