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Validation and Recalibration of the Asbestos Removal Exposure Assessment Tool (AREAT)

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Abstract

Objectives: The Asbestos Removal Exposure Assessment Tool (AREAT) was previously developed to estimate exposure to respirable asbestos fibres during abatement processes. The current study describes the validation and recalibration of the AREAT model with external data. During model validation, the AREAT model was expanded to be able to estimate asbestos exposure from an additional source category: 'unspecified asbestos remnants'.

Methods: The validation dataset (n = 281) was derived from exposure measurement studies where for each exposure measurement the AREAT model parameters were coded and estimates were calculated. Pearson correlation coefficients (r) and intra class correlation coefficients (icc) were calculated as an indication of the agreement between the AREAT estimates and measured concentrations. In addition, the bias and the proportion of measurements with higher concentrations than model estimates were calculated. To expand and investigate model performance on exposure from 'unspecified asbestos remnants', a separate dataset was created with measurements collected during working with unspecified asbestos remnants, and similar validation comparisons were performed. Lastly, linear regression techniques were used to investigate possible improvements in model parameters. The model was recalibrated on a combined dataset consisting of the validation dataset and the original calibration dataset to increase model robustness.

Results: The validation comparisons showed good relative agreement (r) between AREAT estimates and measurements (r = 0.73) and a moderate absolute agreement (icc = 0.53). The overall relative bias was 108%, indicating an overall overestimation of exposure, and 4% of the estimated concentrations were higher than the actual measured concentrations. For the data subset concerning unspecified asbestos remnants, a moderate correlation between model estimates and measurement outcomes was found (r = 0.63). However, based on the low number of data in this subset, and moderate r, it was decided that cleaning of unspecified asbestos remnants is out of scope until more data are available. The results of this validation study suggested that two input parameters (product type friable material, efficacy of control measure foam) underestimated exposure. The effects of these parameters were updated to improve model performance. Compared to the original model, the recalibrated model resulted in slightly higher explained variance (62% compared to 56%) and lower uncertainty (15 compared to 17.3).

Conclusion: The original AREAT model provided reliable asbestos exposure estimates with a sufficient level of conservatism taking into account the 90-percentile estimates. The model was further improved via the addition of a new feature and recalibration to predict asbestos exposure during the clean-up of unspecified asbestos remnants.

Keywords: asbestos model; asbestos exposure; exposure model; linear regression; model validation

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What's Important About This Paper?

The AREAT estimates exposure to respirable asbestos fibres during abatement, and this validation exercise demonstrated satisfactory tool performance. Modifications were made to two input parameters that improved tool performance. The tool can be used to reliably estimate asbestos exposures during abatement activities.

Introduction

Asbestos has been widely recognized as carcinogenic to humans and animals (e.g. Mossman et al., 1983; Barrett et al., 1989; Huang et al., 2011). Although asbestos use in new buildings has been banned for over 40 years in western countries, exposure to asbestos fibres still occurs due to its widespread former applications in residential and industrial buildings. Occupational risks associated with asbestos have shifted to maintenance, installation, and abatement work.

Within the Netherlands, before abatement work is allowed to commence, an exposure assessment needs to be conducted to assign the proper control regime to allow safe working conditions. For situations where no exposure measurements are available, the Asbestos Removal Exposure Assessment Tool (AREAT) was developed and described by Franken et al. (2021). This model is used for exposure assessment when exposure measurements or safe working procedures are not available. The model was developed to estimate the 90th percentile of the exposure distribution and, since its applicability domain is asbestos fibres, it is important that the estimates of the model are conservative. In practice, this means that when the 90th percentile estimate is below the Dutch occupational exposure limit value (OELV) of 2000 asbestos fibres/m^3, by law, abatement processes can be conducted in a lighter control regime.

Validation of existing occupational exposure models is considered an important aspect of model development (Tischer et al., 2017; Schlueter & Tischer, 2020), and are generally conducted for numerous existing exposure models such as ECETOC TRA, Stoffenmanager and the Advanced REACH Tool (e.g. Koppisch et al., 2012; Hofstetter et al., 2013; Spinazzè et al., 2017; Van Tongeren et al., 2017; Savic et al., 2018; Lee et al., 2019). Because the AREAT model is being incorporated in the asbestos legislation in the Netherlands, and its outcomes have practical implications on the control regimes to be applied during asbestos abatement processes, it is important that both the accuracy of the model predictions, as well as the conservativeness of the model are trusted, which expresses a need for validation of the model before being used in practice.

In addition to the validation of the existing AREAT model as described by Franken et al. (2021), a need for expansion of the functionalities of the model was identified. The original AREAT model relies on an input parameter that indicates a specific asbestos containing product type (e.g. elastic materials, asbestos cement materials, or friable materials). However, in practice, clean-up activities of unspecified asbestos remnants occur in many settings. In these cases, the presence/absence of asbestos is verified using adhesive samples. Therefore, the AREAT model was expanded to facilitate the estimation of asbestos exposure from the cleaning of unspecified asbestos remnants.

The goal of the current study was to (i) validate the existing AREAT model, (ii) extend its functionality by adding the option to predict exposure during cleaning unspecified asbestos remnants, and (iii) recalibrate the model with a combined dataset consisting of the validation dataset and the original calibration dataset to increase model robustness.

Methods

The AREAT model

Details of the AREAT model have been described by Franken et al. (2021). In summary, AREAT was developed in several steps, which first a mechanistic model was developed, then a dataset was created from an in-house database with available asbestos exposure measurements, and lastly the model was calibrated by using a statistical model that translates the dimensionless scores from the multiplicative mechanistic model to an actual asbestos fibres concentration estimate by relating these scores to measurement data. AREAT is capable of estimating exposure for workers with the source(s) in the near-field (source <1 m to the workers' breathing zone) and/or the far-field (source >1 m from the workers' breathing zone). The near-field and far-field dimensionless model scores based on multipliers of the mechanistic model are calculated in the following way:

$$C_{nf} = (E_{nf} * H_{nf} * Lc_{1nf} * Lc_{2nf}) * D_{nf} \quad (1)$$

$$C_{ff} = (E_{ff} * H_{ff} * Lc_{1ff} * Lc_{2ff}) * D_{f} \quad (2)$$

where E is defined by the product type (matrix in which the asbestos is incorporated), the sum of the concentrations of chrysotile and amphibole fibres present in the material and the moisture content, H is defined by the activity, Lc_1 and Lc_2 are defined by any local control measures in use during the activity, and D is the dispersion based on the effect of room size and ventilation on personal exposure levels. Finally, C_{nf} and C_{ff} scores are aggregated to one final dimensionless score in which any near-field and/or far-field exposure sources that influence the exposure of the worker are taken into account.

Study overview

This current study consisted of three parts: (i) the validation of the existing AREAT model as presented in Franken et al. (2021), (ii) expanding the model to be able to estimate exposure to asbestos fibres during cleaning of unspecified asbestos remnants, and (iii) adjustment of the algorithm and recalibration of the model with an extended dataset.

Data handling

Occupational exposure data collected during asbestos abatement were extracted from an in-house database. The development of this database and criteria for including measurements have been previously described by Franken et al. (2021). Additional studies were entered into this database following the same protocol and criteria. Measurement data used in the calibration dataset to develop the original AREAT model were excluded from extraction into the validation dataset. All asbestos fibre analyses were conducted with SEM/EDX in accordance with ISO 14966 and only asbestos fibres with lengths greater than 5 μm and widths extending from the calibrated lower limit of visibility of 0.2 μm up to 3 μm were reported in the database (ISO, 2019). The contextual information available for these measurements allowed for all model parameters to be coded for all activities, materials, and environmental circumstances.

Data quality and exclusion criteria and the parameterization of AREAT scores were done as described by Franken et al. (2021). In brief, measurements were included in the dataset when the core information was documented, all modifiers could reliably be assessed or assumed, and relevant site information (such as worker and location IDs). After the entry of the data into the database, all measurements were checked by a different person to ensure consensus on data parameterization.

Franken et al. (2021) described in detail how measurements with results below the limit of detection (LOD) based on the SEM analysis of filter were handled, as well as how these results were used in model development. Briefly, it is difficult to use statistical methods to impute concentrations for measurements with a result <LOD based on the data distribution due to the relatively high percentage of measurements without quantified exposures. AREAT is calibrated with the use of nominal fibre concentrations based on the Poisson distribution. Therefore it is not logical to use the upper limit of 95% confidence interval based on the Poisson distribution around the nominal fibre concentration for handling samples with a result <LOD since these concentrations are generally higher compared to nominal concentrations when actual fibres are counted on the filters. Therefore, for a better representation of nominal asbestos fibre concentrations, for samples with a result <LOD the nominal concentration is estimated assuming that one fibre was counted on the filter.

For the validation study, measurements with a result <LOD were included in the analysis when comparing the AREAT exposure estimates with measured values. For the recalibration of the AREAT, the measurements with a result <LOD were excluded. The main reason is that it was previously found that the uncertainty surrounding these measurement results led to unreasonable performance impairment (Franken et al., 2021).

Validation of AREAT

For all exposure scenarios in the validation dataset, asbestos fibre concentrations were estimated with the AREAT model and its regression coefficients as described in equations (7) and (8) and Franken et al. (2021). Both visual inspection and the Shapiro–Wilk normality test showed that the data are not normally distributed. Therefore, both the geometric mean (GM) and the 90th percentile predictions were calculated. Pearson (r) and intra class correlation coefficients (icc) were calculated to assess relative and absolute agreement between model estimates and measured values. The r is useful to investigate whether the model is capable of distinguishing low from high values, and the icc assesses the absolute agreement between estimated and measured values. The percentage of measurements of whose exposure concentrations were underestimated by model predictions was also calculated.

In addition, model bias was calculated following equation (3) and relative bias was calculated following equation (4), where $\hat{y}$ is the natural log (ln) of the GM predicted exposure level, y_i the ln measured exposure and n_0 the number of measurements in the validation dataset. For both types of biases, positive values indicate a tendency of the model to overestimate measured exposure, and negative values indicate the contrary. In addition to bias, Bland-Altman plots were derived to visualize these trends of over- or underestimation.

$$Bias = \sum_{i=1}^{n0} \frac{\left(\hat{y} - y_i\right)}{n_0} \quad (3)$$

$$Relative\ bias = (e^{bias} - 1) * 100\% \quad (4)$$

Multiple linear regression analysis

Multiple linear regression analysis described by equation (5) was conducted to investigate whether the available measurement data indicated a clear trend of over- or underestimation of exposure by AREAT, which can be related to a certain model input.

$$\ln(\gamma_j) = \sum_{i=1}^{I} \beta_{p,i} * I_{p,j} + \sum_{i=1}^{I} \beta_{h,i} * I_{h,j} + \sum_{i=1}^{I} \beta_{s,i} * I_{s,j} + \sum_{i=1}^{I} \beta_{LC,i} * I_{LC,j} + \sum_{i=1}^{I} \beta_{ACH,i} * I_{ACH,j} + \sum_{i=1}^{I} \beta_{d,i} * I_{d,j} + \sum_{i=1}^{I} \beta_{ca,i} * I_{ca,j} + \sum_{i=1}^{I} \beta_{cc,i} * I_{cc,j} + \epsilon \quad (5)$$

For equation (5), $\ln(\gamma)$ represents the measured fibre concentrations, and β_p, β_h, β_s, β_{LC}, β_{ACH}, β_d, β_{ca} and β_{cc} represent the population effect levels of the product type, task, state of the material, local control measures, ventilation, room volume and asbestos content of the material for both amphibole and chrysotile asbestos, respectively, being type *i (i=1,....,I)* and *I* the indicator variable $I_{p,j}$ to select the correct type for measurement *j (j = 1,....,N)*.

For linear regression analysis in general, it is important that the underlying dataset support the population effects with sufficient data (the more the better). Therefore, for the linear regression analysis, both the validation and the calibration dataset were taken into account, including measurement results <LOD.

Expansion of functionality AREAT to include cleaning of unspecified asbestos remnants

In the original AREAT model, information about both the product type and the type of activity performed are needed to estimate asbestos exposure. For the 'cleaning' activity, it was previously assumed that abatement/cleaning would only occur in settings where the asbestos product type (e.g. asbestos cement materials, friable materials) is known. However, in practice sometimes asbestos-containing contaminants must be cleaned up although the actual source of these contaminants is unknown. In the Netherlands, the general level of contamination, including the presence of loose asbestos fibres, is ascertained using adhesive strips. Usually, several strips are collected per work site and analysed with SEM/EDX in accordance with ISO 14966. Results are expressed with symbols (–, +–, + and ++), which correspond to semi-quantitative categories of surface asbestos concentration (<10, 10–100, >100–1000, >1000 fibres/cm^2).

To be able to estimate exposure during clean-up of asbestos contamination from unknown sources, we introduced a new product type category in the AREAT model named 'unspecified asbestos remnants'. For this category it is assumed that the original type of material, asbestos concentration of that material, and/or the activity with an asbestos containing product that resulted in the contamination is not known. In this case, the substance emission potential (E) in equations (1) and (2) is determined by the analytical results of adhesive samples. As mentioned before, these results are expressed with symbols, for which modifying factors (MFs) were derived. E is then calculated by the multiplication of the product type (P)* MFs derived for the results of adhesive samples of both chrysotile and amphibole fibres ($Cadh_{chrys}$ + $Cadh_{am}$) and the activity emission potential (H). For such cases, only the type of cleaning activity is relevant for determining H.

In a subset of the database, measurements were selected for situations during which the asbestos-containing remnants were cleaned and where this cleaning was the only activity performed during the measurements. Data were taken into account if the level of contamination was determined via adhesive sampling. Since this functionality was not a part of the original AREAT model, the regression model could not be used to calculate concentration estimates. Therefore, dimensionless AREAT scores were compared with the measured exposure concentrations similarly as was done during the development of the original AREAT model. Based on the scatterplot and the Pearson correlation coefficient the performance was assessed.

Model refinement and new calibration

Using a linear mixed effect model (formula 6), AREAT was recalibrated with a combined dataset consisting of the validation dataset and the original calibration dataset (n = 179) excluding the measurements where results were <LOD. In formula 6, γ_{ij} is the estimated fibre concentration from the i^{th} scenario and the j^{th} location, $AREAT - score_{ij}$ is the log-transformed dimensionless model score. β_{0j} is the intercept, and β_1 is the effect of the log-transformed model scores also referred to as the slope (which is fixed at 1). δ_j refers to the random effect from the j^{th} scenario and ε_{ij} to the random effect from the i^{th} location where the j^{th} scenario takes place. It is assumed that δ_j and ε_{ij} are normally distributed with an average of 0 and that σ^2_{bs} and σ^2_{ws}, represent the within- and between-scenario variability of that distribution. The error terms were used to calculate the model uncertainty factor (M) and for estimating the 90th percentile of the exposure distribution.

$$\ln(\gamma_{ij}) = \beta_{0j} + \beta_1 * \ln(AREAT - score_{ij}) + \delta_j + \varepsilon_{ij} \quad (6)$$

$$M = EXP\left[1,285\ \sqrt{\sigma_{bs}^2 + \sigma_{ws}^2}\right] \quad (7)$$

Results

In total, the validation dataset consisted of 280 personal inhalation measurements. The measurements originated from 38 individual study reports, and 65% (n = 181) of the measurements had a result <LOD. Generally, the measurements in the validation dataset were reasonably distributed over the different product types. However, it must be noted that the number of measurements was quite low for the group 'Synthetic materials or imitation marble', and no data were available for 'friable materials' (see Table 1). Generally the GM asbestos concentration levels were similar (and low) for product types 'Synthetic materials or imitation marble', 'Elastic materials', 'Woven/pressed materials' and to a lesser extent 'Asbestos cement materials', and concentrations were higher for the 'Loosely bound materials'. These exposure distributions of the validation dataset were fairly similar compared to the original calibration dataset described by Franken et al. (2021).

Calculated exposure estimates were plotted and compared against the measured fibre concentrations (see Fig. 1), where the solid line represents the 'line of equality' (1:1 line based on GM) and the dashed line represents the 90th percentile. Any datapoints above the dashed line represent an underestimation of the 90th percentile exposure level by means of AREAT compared to the measured concentrations. Measured exposure values were underestimated in 4% of all cases (n = 11), and varied between 0–13% between the different product types. For loosely bound materials, 13% of the exposure estimates underestimated the true exposure values, indicating that AREAT estimates were not conservative enough for this particular product type. An overall Pearson correlation (r) of 0.73 and an overall intra class correlation coefficient (icc) of 0.53 were calculated between the estimated and measured concentrations.

Table 2 shows the validation results for the individual product types in AREAT. Correlation coefficients were adequate for most product types with the exception of synthetic materials or imitation marble. In addition to the validation criteria, the relative bias of AREAT was calculated to be 108%. Bias was also calculated for the individual product types. For each category, the bias was relatively close to zero (−67 to 22%) with the exception of woven/pressed materials, which had a high relative bias of 874%.

Figure 2 shows the residual plots for the overall data and separated for values below and above LOD. A slight trend can be observed for residuals of the overall data (R^2 = 0.13), which is largely explained by the values below LOD (R^2 = 0.97). Generally, no significant trend for under- or overestimation by AREAT is found for values above the LOD (R^2 = 0.026).

Figure 3 shows the relation between dimensionless AREAT scores and measured fibre concentrations for a subset of measurements during which unspecified asbestos remnants were cleaned up, and AREAT scores were calculated based on results of adhesive samples. The correlation coefficient was calculated to be 0.63. Based on these results, and the number of measurements available for this addition to AREAT, it was decided not to include the clean-up of unspecified asbestos remnants in the AREAT model until more measurements are available, and a better relationship can be derived. Therefore, this data were not used for recalibration of the model.

Based on the linear regression analysis using equation (5) on the combined calibration and validation dataset (summary statistics are shown in Table 3) the effects of model determinants on exposure were investigated.

Table 1. Summary statistics of the validation dataset per product group (in asbestos fibres/m^3)

Product type	N (N < LOD)	AM	GM	GSD	Range
Synthetic materials or imitation marble	12 (12)	62	62	1.0	59–65
Elastic materials	93 (75)	175	80	2.4	29–3908
Asbestos cement materials	49 (26)	30,730	745	24.1	32–397,698
Woven/pressed materials	96 (60)	4378	133	4.8	32–212,014
Loosely bound materials	30 (8)	629,435	4478	80.4	66–6,500,000
Friable materials	0				
Total	280 (181)	74,379	214	13	29–6,500,000

N, number of measurements; N < LOD, number of measurements with results <LOD; AM, Arithmetic mean; GM, geometric mean; GSD, geometric standard deviation.

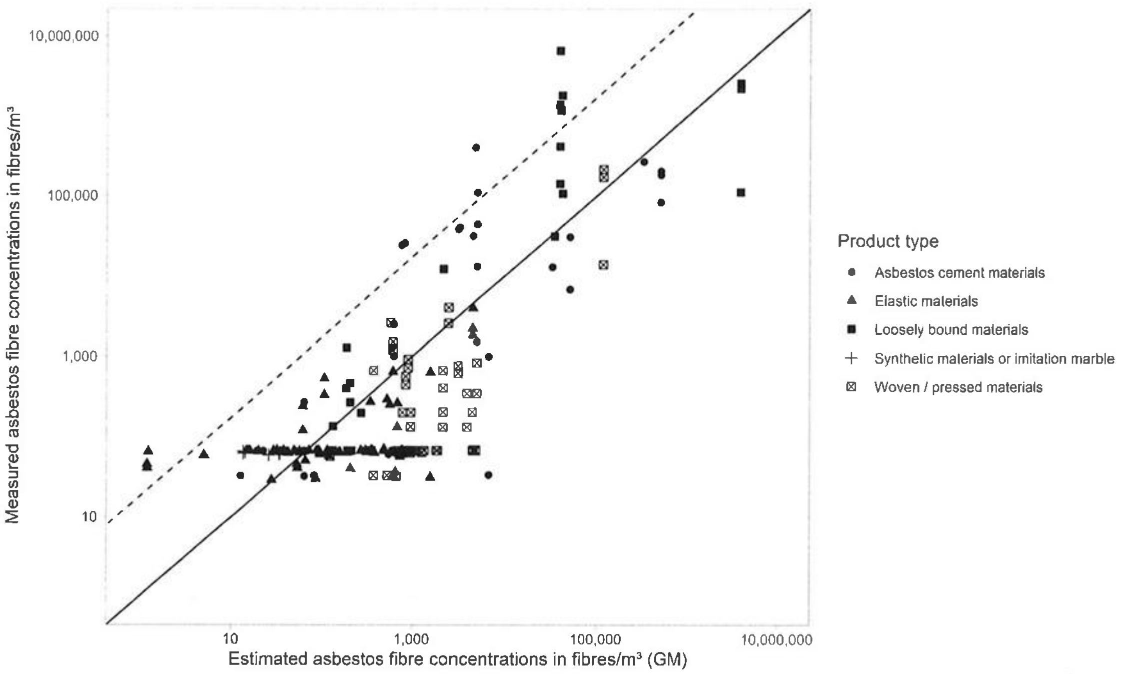

Figure 1. AREAT estimated asbestos fibre concentrations compared to measured asbestos fibre concentrations with the (solid) 1:1 line and the (dashed) 90th percentile line (concentrations is in fibres/m³).

Table 2. Results of the validation, separated for each product type

Product type	*r* (95% CI)	Bias	Relative bias (%)	% > 90th percentile
Synthetic materials or imitation marble	−0.65 (−0.89–−0.11)	−1.12	−67.6	0
Elastic materials	0.49 (0.32–0.63)	0.2	22.0	3
Asbestos cement materials	0.82 (0.7–0.89)	−0.03	−2.6	8
Woven/pressed materials	0.65 (0.51–0.75)	2.28	874.0	0
Loosely bound materials	0.9 (0.8–0.95)	−0.25	−22.2	13
Total	0.73 (0.67–0.78)	0.73	107.5	4

r, Pearson correlation coefficient; % > 90th percentile, number of measurements exceeding the AREAT 90th percentile estimate.

Table 4 and Fig. 4 show the results of this linear regression analysis for the model determinants taken into account as well as their original AREAT multipliers and significance ($P < 0.05$).

The results of the linear regression analysis are presented in Table 4. Overall, the model has an adjusted r^2 of 0.8, which is considered high. This highly explained variance by the multiple linear regression analysis shows that we have selected relevant exposure determinants for the AREAT model.

With regards to the product type, from the results of the analysis it can be observed that generally the effects are incrementing along the lines of the multipliers assigned to the different product types (which is among others based on the level of friability of the different materials), with the exception of 'Woven/pressed materials', which appear to have a stronger effect, and 'loosely bound materials', which appears to have an effect similar to 'asbestos cement materials'.

The state of the material is also positively correlated with exposure and shows a significant higher effect for materials that are considered to be in a poor state (e.g. damaged or weathered materials).

With regards to the concentration ranges for both chrysotile and amphibole asbestos, a general incrementing effect can also be observed for the concentration ranges, where the effect on exposure is higher for higher concentration ranges. In addition, it appears that working with amphibole asbestos results in higher exposure values compared to working with

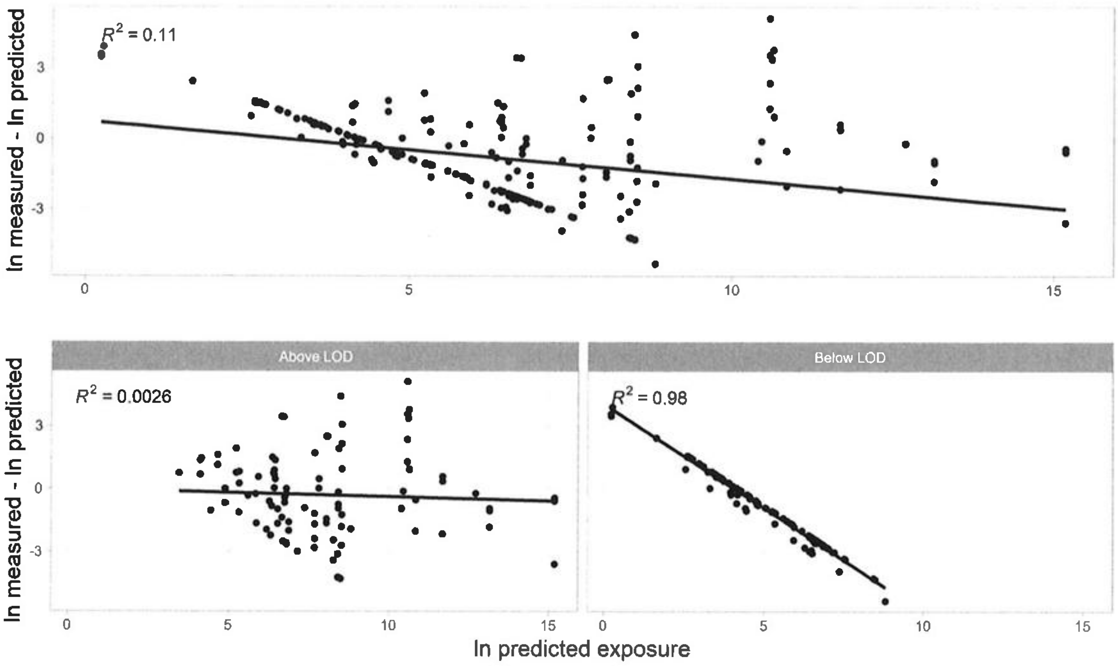

Figure 2. Residual plot separated for values below the LOD.

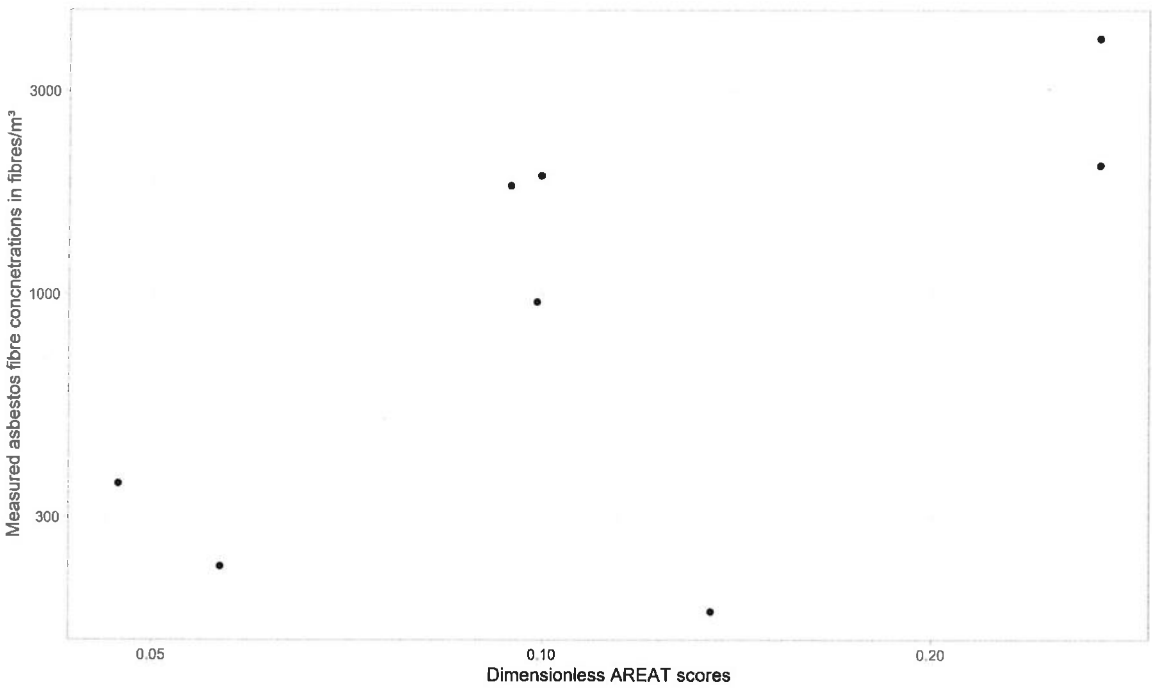

Figure 3. Dimensionless AREAT scores compared to measured fibre concentrations for clean-up activities.

Table 3. Summary statistics of the validation and calibration dataset combined per product group

Product type	N (n<LOD)	AM	GM	GSD	Range
Synthetic materials or imitation marble	45 (33)	185	132	2.2	59–970
Elastic materials	182 (140)	452	162	3.7	29–6600
Asbestos cement materials	138 (85)	11,405	306	9.57	30–397,698
Woven/pressed materials	146 (82)	12,737	242	8.03	32–966,000
Loosely bound materials	133 (28)	3,796,172	14,527	56.3	30–126,960,000
Friable materials	6 (0)	9,246,667	1,549,573	2.34	286,000–50,780,000
Total	650 (369)	867,531	546	21.7	29–126,960,000

N, number of measurements; N < LOD, number of measurements with results <LOD; AM, Arithmetic mean; GM, geometric mean; GSD, geometric standard deviation.

chrysotile asbestos, which is in line with AREAT assigning a factor two higher multiplier effects to concentration ranges concerning amphibole asbestos.

With regards to controlling measures, it can be observed that all controls have a significant effect on reducing the exposure levels during abatement processes. Furthermore, it can be observed that, according to the regression analysis, LEV and surface wetting have the smallest effect and thorough wetting has the highest effect, which fits with the multipliers chosen for these controls. In the original AREAT model, the control measure 'foam' was assigned the highest multiplier (=0.01), which is not reflected in the regression analysis.

With regards to tasks, it can be observed that the effect on exposure from the differences in the way materials are handled (careful, normal, or rough handling) is also visible from the results of the regression analysis. A similar effect is visible for the differentiation of the amount of damage occurring during disassembly activities, although the difference between minimal and little damage is not apparent. Cutting with electric equipment seems to result in slightly higher exposure compared to manual cutting.

For ventilation and room volume, for which multipliers in AREAT are a result of the combination of the two parameters, it can be observed that outdoor activities have a significant effect on (reducing) exposure. Unfortunately, not all categories of room volume are present in the database, which means we cannot determine the effect of the volume of the room on exposure. In addition, higher ventilation rates seem to be a predictor for higher exposures according to the analysis. This can be explained however by correlated data, as in reality, abatement processes where exposures are expected to be low are performed in conditions with relatively low ventilation rates and processes where exposures are expected to be high are generally performed in enclosures with high ventilation rates.

Based on the results of the validation of AREAT, the regression analysis, as well as expert knowledge, two multipliers were changed. The multiplier for the local control 'use of foam' was changed from 0.01 to 0.03 for more friable materials (product types woven/pressed, loosely bound materials and friable materials), and the effect remains 0.1 for non-friable materials (product types synthetic materials or imitation marble, elastic materials and asbestos cement materials). The multiplier for friable materials was adjusted from 3 to 10 based on observations from a calibration plot (not shown here but similar to Fig. 1) with AREAT scores plotted against measured values using original calibration values and new validation values. Here we noticed that all datapoints were above the GM line and sometimes above the 90th percentile line, indicating that future AREAT estimates for friable materials underestimate true exposures. Taking into account the low number of available datapoints for friable materials, we deemed it necessary to adjust the value to ensure conservative exposure estimates for this product type.

Next, the AREAT model was recalibrated using measurements from the original calibration dataset and the validation dataset. The results of the statistical model describing the relationship between AREAT scores and measured fibre concentrations are presented in Table 5. Model A represents the model without any fixed effects (the empty model). Model B represents the model where the AREAT scores are used as fixed effects and where the slope (β_1) is fixed on 1 (as was the chosen approach for the original model as well), leading to proportional model scores compared to actual exposure levels. The results for the original model as well as the new model are presented. For the new model, the explained variance and the uncertainty factor (UF) improved (explained variance 62% compared to 58% and UF 15 compared to 17.3). The intercept (β_0) is slightly lower, but very similar compared to the old model as well. This means that the relationship between AREAT dimensionless scores and measured

Table 4. Results of the linear regression analysis predicting asbestos fibre concentrations with several AREAT determinants as predictors compared with original AREAT multipliers

Predictors	Original AREAT multiplier	Estimates (β)	Confidence interval (CI)	P
(Intercept)		4.92	3.49 to 6.34	<0.001*
Product				
Synthetic materials or imitation marble (reference)	0.03	0	0	0
Elastic material	0.1	0.38	−0.87 to 1.63	0.552
Asbestos cement materials	0.3	1.01	0.43 to 1.6	0.001*
Woven/pressed materials	0.3	2.5	0.64 to 4.35	0.008*
Loosely bound materials	1	0.85	−0.51 to 2.21	0.222
Friable materials	3	1.9	−0.88 to 4.67	0.18
State				
Good state of product (reference)	1	0	0	0
Moderate state of product	3	0.99	0.56 to 1.43	<0.001*
Task				
Wetting low pressure (reference)	0.01	0	0	0
Wetting high pressure	10	6.96	3.95 to 9.97	<0.001*
Careful handling	0.01	−0.65	−1.95 to 0.65	0.325
Normal handling	0.1	2.31	1.24 to 3.39	<0.001*
Rough handling	1	4.96	3.7 to 6.21	<0.001*
Cutting with electric equipment	3	2.08	0.6 to 3.56	0.006*
Cutting using manual equipment	1	1.4	0.05 to 2.75	0.042*
Disassembly with minimal amount of damage	0.01	1.28	0.16 to 2.41	0.026*
Disassembly with little amount of damage	0.1	0.64	−0.42 to 1.71	0.237
Disassembly with moderate amount of damage	1	1.49	0.47 to 2.51	0.004*
Disassembly with high amount of damage	10	5.11	4.14 to 6.08	<0.001*
Manual abrasion of materials resulting in very limited release of fibres	1	0.99	−0.24 to 2.23	0.114
Manual abrasion of materials resulting in limited release of fibres	3	1.84	0.51 to 3.17	0.007*
Mechanical abrasion of materials resulting in limited release of fibres	3	1.31	−0.11 to 2.72	0.070
Mechanical abrasion of materials resulting in substantial release of fibres	30	3.03	1.37 to 4.69	<0.001*
Mechanical cleaning	0.1	2.71	0.43 to 4.99	0.020*
Controls				
No controls (reference)	1	0	0	0
LEV	0.7	−1.11	−1.6 to −0.61	<0.001*
Surface wetting	0.3	−0.64	−1.12 to −0.15	0.010*
Thorough wetting	0.03	−3.46	−4.59 to −2.33	<0.001*
Foam	0.01	−1.63	−2.08 to −1.18	<0.001*
Ventilation				
0.3 ACH (reference)	*Na*	0	0	0
1 ACH	*Na*	−0.52	−0.9 to −0.15	0.006*
6 ACH	*Na*	1.16	0.51 to 1.81	0.001*
Volume				
Indoor–<30 m³	*Na*	0	0	0
Indoor–30–100 m³	*Na*	0.41	−0.03 to 0.86	0.070
Outdoor	*Na*	−1.41	−1.99 to −0.83	<0.001*

Table 4. Continued

Predictors	Original AREAT multiplier	Estimates (β)	Confidence interval (CI)	*P*
Chrysotile concentration				
<0.1% (reference)	0	0	0	0
0.1–2%	0.01	−1.75	−2.59 to −0.92	<0.001*
2–5%	0.035	−1.24	−1.93 to −0.54	<0.001*
5–10%	0.075	−0.45	−2.42 to 1.52	0.651
10–15%	0.125	−0.5	−1.43 to 0.43	0.292
15–30%	0.225	−1.08	−2.44 to 0.28	0.119
30–60%	0.45	−0.13	−1.84 to 1.57	0.877
>60%	0.8	−0.47	−2.2 to 1.26	0.594
Amphibole concentration				
<0.1% (reference)	0	0	0	0
0.1–2%	0.02	−0.57	−1.23 to −0.1	0.094
2–5%	0.07	−0.27	−0.95 to 0.41	0.435
5–10%	0.15	−1.90	−3.76 to −0.03	0.046*
10–15%	0.25	0.04	−1.64 to 1.72	0.962
15–30%	0.45	1.43	−0.05 to 2.91	0.058
30–60%	0.9	3.26	1.68 to 4.85	<0.001*
>60%	1.6	5.1	2.5 to 7.69	<0.001*
R^2	0.8			
R^2 adjusted	0.78			

*Significant effect.

fibre concentrations remain similar compared to the first calibration of the AREAT model.

Discussion and Conclusions

This work presents the validation and recalibration of the AREAT model, and the addition of cleaning of unspecified asbestos remnants in this model. The validation showed that the original AREAT model was sufficiently conservative, bias is acceptable and exposure estimates were sufficiently in agreement with measured asbestos fibre concentrations. In addition, the AREAT model is moderately capable of estimating exposure in situations where both specified and unspecified asbestos remnants are cleaned up.

With regards to the estimation of exposure situations where unspecified asbestos remnants are cleaned up, the number of available measurements for this new function were low (n = 8). Therefore it was decided to exclude this exposure scenario's from AREAT until more exposure data are available to underpin this feature.

The number of measurements for friable materials is also low (n = 6). Despite this, it is important to keep this category in the model, as handling materials like spray-on asbestos are very likely to result in more emission of asbestos fibres than other less friable materials like those for product type 'loosely bound materials' due to different product characteristics (e.g. more loose matrix), which could result in underestimating exposure levels. In addition, recalibration of the model with the adapted score for friable materials showed an improvement in both explained variance and model uncertainty. This indicates that our observations indicated in the result sections were correct and a higher score for friable materials is appropriate.

When comparing the results of this current study with previous validation studies, the correlation between estimated and measured exposure concentrations was high (r = 0.79) compared with other exposure models, such as ECETOC TRA v3 (volatile liquids r = 0.34; metal abrasion r = −0.32 and powder handling r = 0.68) and Stoffenmanager (volatile liquids r = 0.55; non-volatile liquids r = 0.62 and powder handling r = 0.83) (Lamb et al., 2015; Van Tongeren et al., 2017). The differences may be explained by the applicability domains of the different models, as the AREAT model is tailored towards

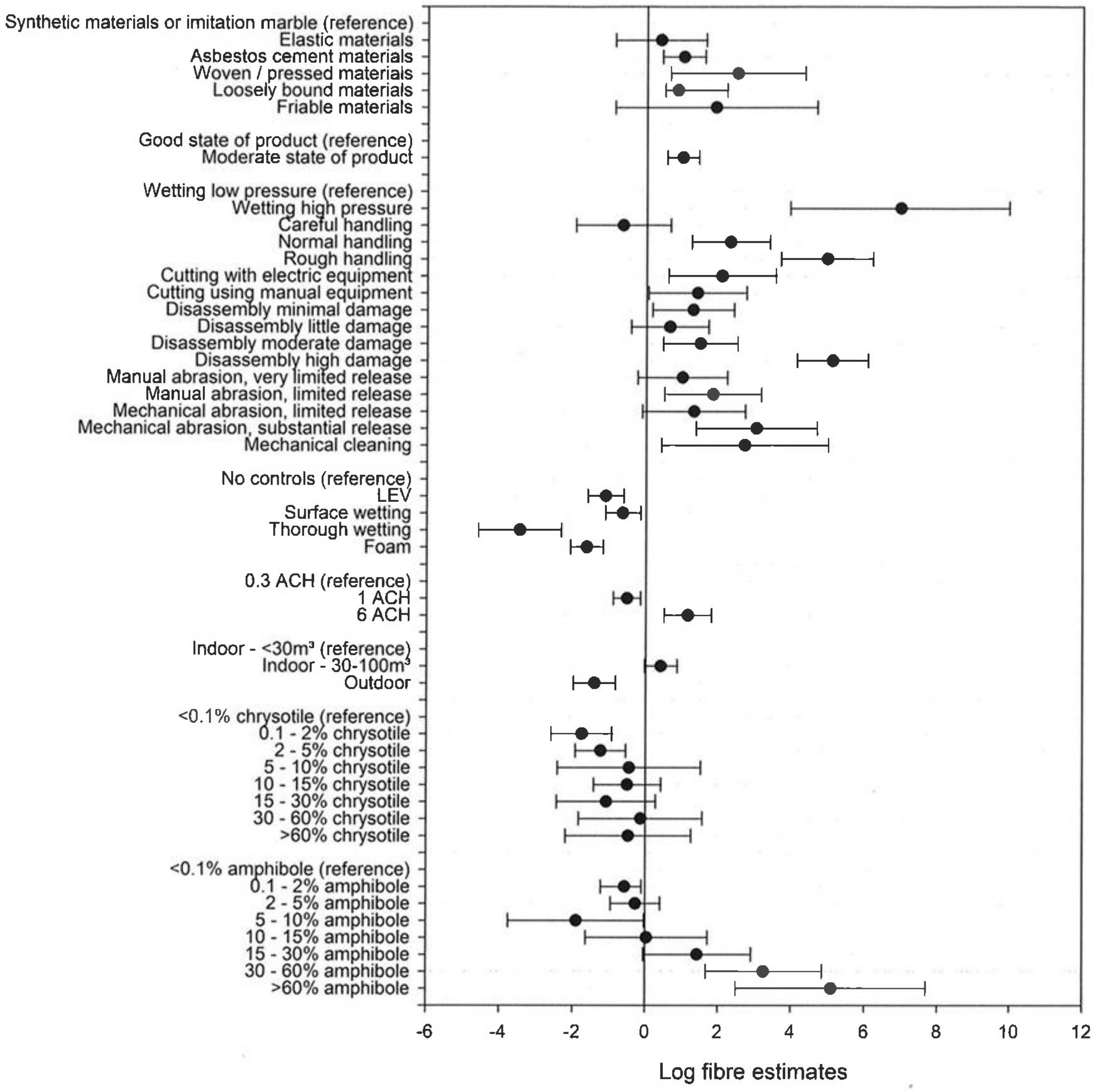

Figure 4. Results of the multiple linear regression analysis visualized (note that some determinant names have been shortened for readability of the figure).

asbestos removal processes, and the applicability domains of Stoffenmanager and ECETOC TRA cover various industrial and professional processes. Schinkel et al. (2010) described a trade-off between the broadness of its application and the accuracy of the model, which is visible in the validation results here. Another notable difference between the AREAT model and other exposure models is the level of conservativeness. Our validation results showed that overall 4% of the results of exposure measurements exceeded the 90th percentile model predictions, while in several other validation studies it was concluded that both Stoffenmanager and ECETOC TRA v3 are not always conservative enough. For example, in case of Stoffenmanager exceedance of 16% for non-volatile liquids and 13% for volatile liquids, and in the case of ECETOC TRA v3 exceedance of 35, 44 and 28% for volatile liquids, metal abrasion and powder handling respectively (Lamb et al., 2015; Van Tongeren et al., 2017). AREAT is developed to estimate exposure to asbestos fibres in the Netherlands and is implemented in a tool that assigns the control regime to be applied based on the (estimated) asbestos exposure. Use of this tool to determine the necessary control regime is mandatory for companies before they are allowed to start the asbestos removal work. As asbestos is a carcinogen,

Table 5. Results of the linear mixed effect models for recalibration of the AREAT model

Model	N	β_0	β_1	σ^2_{bs}	σ^2_{ws}	Explained variance (%)	UF
A (original)	179	8.39	n.a.	9.6	1	n.a.	n.a.
B (original)	179	11.59	1	3.79	1.14	58	17.3
A (new)	281	7.73	n.a.	9.86	2.1	n.a.	n.a.
B (new)	281	11.41	1	2.75	1.7	62	15

A, an empty model; B, the model with AREAT scores as fixed effects and projectID and containmentIDs as random effects; N, number of measurements used for calibration; β_0, The intercept; σ^2_{bs}, The between scenario variance; σ^2_{ws}, The within scenario variance; UF, The model uncertainty factor.

it was considered very important that AREAT would be conservative enough to guarantee worker health.

The results of the linear regression analysis, when compared with the AREAT multipliers assigned to all model parameters, proved a useful tool to help identify possible adjustments to the model that would lead to improved predictions. However, the results of the analysis need to be interpreted with caution since these results are heavily reliant on the contents of the database used. For example, the results from the linear regression analysis seem to suggest that when the ventilation rate in the room is high, the exposure is high, although in general lower exposure values are expected with higher ventilation rates. However, in practice many exposure studies are performed to prove that the OELV for asbestos is not exceeded when a specific abatement process is applied (thus: low exposure values are expected). Within these exposure studies, it is mandatory that a low ventilation rate is applied (between 0.1 and 1 ACH) to mimic the desired practical situation (no containment). This means that in general studies in which low exposure levels are measured are performed in containments with low ventilation rates, while studies where exposures are expected to be high are always performed in containments with high ventilation rates. This might explain why the results of the regression analysis suggest high exposures when the ventilation rate is high. Additionally, the effect of the product type 'woven/pressed materials' was quite high which seems not in line with the theoretical MF assigned in AREAT. However, in practice, woven/pressed materials (often gaskets in the database) are often removed in combination with the control measure thorough wetting, which had a very high exposure reduction effect in the regression analysis. These two parameters (woven/pressed materials and thorough wetting as control) are expected to be correlated in the database and might explain the results from the linear regression analysis. Such knowledge with regard to the content of the underlying data are essential when interpreting the results of the linear regression analysis. Therefore, the results of this analysis were only used indicatively. Adjustments of the AREAT model based on the results of this analysis were only made when the developers of AREAT agreed with the changes based on their experience and expert judgement.

It was observed that the relative bias was negative for the product type 'synthetic materials or imitation marble' as well as a low correlation coefficient, which can be explained by the low variance of exposure for this category (59–65 fibres/m^3). Moreover, the bias with regard to the product type 'woven/pressed materials' was high (874%), which could not really be explained. In a lot of these scenario's the local control measure 'thorough wetting' is applied, which in practice consists of a specific technique that is usually applied when removing gaskets, that assures the materials are impregnated with water continuously. It might be possible that this specific technique increases the effectiveness of the local control measure which is not accounted for in the AREAT model. However, currently we do not have enough data to support this enough to make changes to either the category 'woven/pressed materials' or the local control 'thorough wetting'. In addition, the validation results showed that model estimates for the product type 'loosely bound materials' underestimated measured exposure values in 13% of the cases, which suggested that adjustments were needed here. However, with the change of the multiplier for the local control 'use of foam' from 0.01 to 0.03 for more friable materials, some of the estimates which previously underestimated true exposure have increased. This change resulted in an underestimation of 6% for the 'loosely bound materials', and this category was therefore not changed.

In conclusion, the AREAT model was validated by comparing model estimates with the results of exposure measurements. The validation showed a good correlation between estimated and measured asbestos fibre concentrations, and the AREAT predictions were considered to be conservative as <5% of the 90th percentile model estimates were underestimated by measured exposure values. In addition, the applicability domain of the model has been expanded and now also includes cleaning of unspecified asbestos remnants. With the recalibration of the AREAT, a new validation exercise is required to further test the model with an additional dataset.

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Conflict of interest

The authors declare no conflict of interest relating to the material presented in this Article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

Data availability

The data underlying this article cannot be shared publicly as the data are owned by many different third parties (abatement companies) who shared their data with TNO for the analysis.

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