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Prevalence of skin sensitization and dermatitis among epoxy-exposed workers in the wind turbine industry*

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Summary

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Background A high prevalence of skin sensitization and dermatitis has been reported among workers exposed to epoxy components.

Objectives To estimate the risk of skin sensitization and dermatitis among workers exposed to epoxy components during production of wind turbine blades while using comprehensive safety measures.

Methods A cross-sectional study of 180 highly epoxy-exposed production workers and 41 nonexposed office workers was conducted at two wind turbine blade factories in Denmark. Participants underwent a skin examination, were tested with a tailored patch test panel including epoxy-containing products used at the factories, and answered a questionnaire.

Results Sixteen production workers (8.9%) were sensitized to an epoxy component compared with none of the office workers. Skin sensitization was more frequent within the first year of exposed employment. Strong selection bias by atopic status was indicated. Among nonatopic workers, the prevalence of dermatitis was higher among production workers (16.4%) than among office workers [6.5%, odds ratio (OR) 2.3, 95% confidence interval (CI) 0.6–9.1] and higher among the sensitized workers (43.8%) than the nonsensitized workers (14.6%, OR 4.5, 95% CI 1.6–12.7). Resins based on diglycidyl ether of bisphenol A and F were the most frequent sensitizers. One of the four workers sensitized to epoxy components used at the factories did not react to the epoxy resin of the TRUE test[®] panel.

Conclusions Despite comprehensive skin protection, sensitization and dermatitis are prevalent among highly epoxy-exposed workers in the wind turbine industry in Denmark. Our findings document the need for intensified preventive efforts and emphasize the importance of tailored patch testing.

What is already known about this topic?

- Epoxy components are well-known sensitizers of the skin.
- A high prevalence of skin sensitization and dermatitis has been reported among workers exposed to epoxy components.
- Comprehensive protective equipment is recommended when working with epoxy components.

What does this study add?

- Despite comprehensive skin protection, skin sensitization and dermatitis are prevalent among epoxy-exposed workers.
- We found that 40% of workers sensitized to epoxy products had dermatitis.
- Only 75% of the sensitized workers were detected by the epoxy resin of the TRUE test[®], which emphasizes the importance of tailored testing.

Epoxy resin systems are materials with high mechanical, chemical and thermal resistance. They are widely used as components of protective surfaces, adhesives and paints and in the manufacturing of composites in the plastics industry. Epoxy resin systems consist of resins, hardeners, reactive diluents and additives (hereafter named epoxy components).^{1,2} All components can cause sensitization of the skin, resins being the most frequent sensitizers and one of the leading causes of occupational allergic contact dermatitis.^{3,4} In Denmark in 2010, epoxy resins were found to be the second-most common cause of occupational allergic contact dermatitis.⁵ A 2004 study from the wind turbine industry showed that 10–5% of all participating workers were sensitized to epoxy resins, 20–50 times the prevalence in the general population.^{6–10}

Approximately 75% of epoxy resins are derived from bisphenol A and epichlorohydrin, also known as diglycidyl ether of bisphenol A (DGEBA).¹¹ DGEBA-resins (DGEBA-R) are strong sensitizers of the skin, owing to DGEBA. The content of DGEBA in epoxy resins varies and the DGEBA polymers are described by different Chemical Abstracts Service (CAS) numbers, e.g. 25068-38-6 and 25085-99-8.¹² Epoxy resins are often also based on diglycidyl ether of bisphenol F (DGEBF). Concomitant reactions to DGEBF resin (DGEBF-R, CAS numbers 28064-14-4 and 9003-36-5) and DGEBA-R are well known, owing to cross-reactivity.¹³

In many industries, good alternatives to epoxy resin systems are lacking, and the prospect of finding a suitable substitute in the near future is not very realistic. In fact, the use of epoxy resin systems is expanding.^{14,15} An increase in sensitization to epoxy resins has been observed in the construction industry in Germany during recent years.¹⁵ Therefore, for several years, considerable attention has been devoted to regulation, education, substitution, new procedures and protective equipment. However, little is known about the risk of skin sensitization and dermatitis when using comprehensive protective measures.

We conducted a cross-sectional study in the wind turbine industry which examined the prevalence of skin sensitization and dermatitis among highly epoxy-exposed production workers who used comprehensive safety measures compared with nonexposed office workers.

Materials and methods

Study population

In September 2018, we invited epoxy-exposed production workers from two factories in Denmark (Factory 1 and Factory 2) that produced wind turbine blades. The workers were all involved in manual lamination or filling procedures with expected high risk of skin contamination. During meetings at the factories, all production workers were informed about the study by A.G.C. and were personally handed information leaflets. Office workers at the two factories and at the Department of Occupational Medicine, Aarhus University Hospital were invited via their work email address to participate as a nonexposed control group. Office workers at Factory 1 worked close to the production site and had prior knowledge of the study, whereas office workers from Factory 2 worked far away from the production site with no prior knowledge of the study.

In October 2020, participating production workers at Factory 1 were invited by private email for a follow-up. As a result of downsizing, only a few production workers at Factory 2 remained employed and they were not invited for follow-up.

The study was registered at the repository of the Central Denmark Region (j.nr 2012-58-006).

Work procedures and personal protective equipment

During the lamination procedure, large casting defects of the wind turbine blades are removed with an angle grinder. The defects are repaired by hand lamination. Clear liquid epoxy is applied on fiberglass mats using a handheld roller. Each worker uses a few kilograms of epoxy resins daily. During the filling procedure, small casting defects are filled with a viscous epoxy filler and smoothed with a scraper. This procedure is physically demanding and entails close contact with the resins and carries a high risk of spilling. Each worker uses about 15 kg of epoxy filler daily. During both procedures, workers wear a protective suit with a hood, a face shield, protective glasses, safety shoes, and often an apron, protective arm sleeves and chemically resistant disposable nitrile-rubber gloves. Glove

thickness varies from 0.12 mm to 4.2 mm depending on the processes involved. All gloves are tested at a laboratory for permeability against the relevant products. Thin gloves were tested to provide protection for 0.5–8 h and were never used for more than 0.5 h. Thick gloves were tested to provide protection for 8 h and were changed every second hour.

In Factory 1, workers did either lamination or filling, whereas in Factory 2, workers rotated between the two procedures. In the analyses, we classified the rotating workers of Factory 2 together with the filling workers of Factory 1 because of the higher exposure load of the filling process.

Questionnaire

The questionnaire was a shortened version of the Nordic Occupational Skin Questionnaire^{16–18} containing questions on former and current rashes (on hands, wrists and forearms), allergies, history of atopic dermatitis in childhood, asthma, respiratory symptoms and rhinitis. Questions about exposure to epoxy resins were added. We defined atopy by the presence of atopic dermatitis during childhood.

Patch testing and clinical examination

Production workers were patch tested from December 2018 to March 2019 and September 2019 to November 2019 at Factory 1 and 2, respectively. The production workers of Factory 1 were retested in May 2021 to identify new cases of sensitization and to assess the persistence of sensitization detected at baseline.

Office workers were tested only once from November 2019 to September 2020. Production workers and office workers at Factory 1 and Factory 2 were tested with the nine and the 13 epoxy products that were handled at each of the two factories. Six office workers from the Department of Occupational Medicine were tested as participants from Factory 1 and four were tested as participants from Factory 2.

Before the patch tests were prepared, we performed a thorough review of all products included. Thus, we reviewed the sensitizing potential of all components in a product and set the patch test concentration based on the component with the strongest sensitization potential. We took into account which patch test concentration the various chemicals have in commercial patch test series and used a security factor of two for products containing DGEBA and DGEBF. For example, if epoxy resin bisphenol A was present at or above 50% and epoxy resin, bisphenol F up to 10–25%, the patch test concentration of that work product was set to be 0.5%, as epoxy resin bisphenol A is tested at 1.0% in baseline panels and epoxy resin bisphenol F is tested at 0.25% in epoxy panels. The test materials were diluted in petrolatum. All test preparations were prepared at the Department of Occupational and Environmental Dermatology, Malmö, Sweden.

In order to identify specific allergic reactions, participants (production workers and office workers) from Factory 1 with a positive patch test for epoxy products were additionally

tested with bisphenol A and a series of 15 specific epoxy allergens (Chemotechnique Diagnostics, Vellinge, Sweden) (Table S1; see Supporting Information). Participation during this second step was low. At Factory 2, we therefore tested all participants with bisphenol A and six selected allergens from the epoxy series at the same time as the work products. We restricted testing to these six allergens that were declared for the products used by the workers to keep the potential risk of sensitization low.

Participants were also tested using the Thin-Layer Rapid Use Epicutaneous (TRUE) test[®] panel 1–3, containing DGEBA-R and 34 other allergens (SmartPractice, Hillerød, Denmark) supplemented with the following five additional nonepoxy allergens frequently occurring in work materials: benzoisothiazolinone, methylisothiazolinone, formaldehyde, iodopropyl butylcarbamate (SmartPractice, Calgary, Canada) and 2-n-octyl-4-isothiazolin-3-one (Chemotechnique Diagnostics, Vellinge, Sweden) (Table S2; see Supporting Information).

Finn Chambers (Ø 8 mm) (SmartPractice) on Scanpor[®] tape (Norgesplaster A/S, Vennesla, Norway) were used for the test substances. For allergens in petrolatum, 20 mg was applied, whereas the amount applied for aqueous solutions was 15 µL on a paper filter.¹⁹

Patch testing was performed on site during work hours. Test materials were placed on the upper back and occluded for 48 h. If the back was not suitable, outer upper arms or thighs were used as an alternative (15 participants) as recommended by the European Society of Contact Dermatitis.¹⁹ Two readings, preferably on day (D)4 and D6, were performed by an experienced biomedical laboratory technician. Readings were graded according to criteria established by the European Society of Contact Dermatitis.¹⁹ Readings coded as +, ++ or +++ were all considered as positive in dichotomized analyses. Photodocumentation of the participant's back was made before application of the tests and at the readings. In case of patch test reactions later than D6, the participants were instructed to report and photodocument the reaction.

Clinical skin examination of the hands, upper extremities and truncus for signs of dermatitis (dryness, chapping, redness, infiltration, papules, vesicles and hyperkeratosis) was performed by the A.G.C. prior to patch test application. Dermatitis was defined as either self-reported dermatitis within 12 months based on the questionnaire or dermatitis present at the clinical examination.

We informed only the participants and not the employers about findings for the individual participants. We are aware that many of the sensitized individuals informed their employers and were transferred to nonexposed jobs within the factories, but we did not systematically collect this information.

Ethical considerations

Active sensitization is a potential adverse event when patch testing. Existing literature shows that the risk is minimal, when testing with commercially available allergens.^{20–23} In

Denmark, more than 20 000 persons are tested annually with DGEBA-R included in a baseline series, which is an approved medical product. When testing with work products the risk is higher and a thorough review of the work products was performed. Patch test concentration was determined on the basis of concentrations used in commercial patch tests or as recommended in previous literature.²⁴ Furthermore, a security factor of two was used in products containing DGEBA or DGEBAF in order to minimize the risk of active sensitization as described above.

The Regional Ethical Committee has approved the study (1-10-72-52-18). All individuals were informed about the risk and gave informed consent before inclusion.

Statistical analyses

We computed prevalence of sensitization and dermatitis at baseline and follow-up and estimated odds ratios (ORs) with 95% confidence intervals (CIs) for both endpoints using penalized likelihood analysis.²⁵ Stratified analyses were performed to evaluate the possible modifying effect of atopy. Sex was unequally distributed across exposure status, and we performed sensitivity analyses of men only. Participation rate was very low among office workers from Factory 2, and we also performed sensitivity analyses excluding all participants from Factory 2. Statistical analyses were performed using Stata version 17.0 (StataCorp, College Station, TX, USA).

Results

In total, 447 exposed production workers were invited to participate in the study (Table S3; see Supporting Information). In total, 180 (40.3%) consented and were patch tested: 153 (43.3%) from Factory 1 who performed filling or lamination operations and 27 (28.7%) from Factory 2 who performed mixed filling and lamination operations. Of the 1481 invited nonexposed office workers, 41 (2.8%) consented and were patch tested: 16 (21.3%) from Factory 1, 15 (1.1%) from Factory 2 and 10 (38.5%) from the Department of Occupational Medicine. Twenty-one (13.7%) patch tested production workers from Factory 1 participated at follow-up.

Twenty participants were absent at one reading. Photodocumentation of the reaction on the missing day was provided by nine participants (two were epoxy sensitized); the remaining participants had only one reading at either D4 (seven, with one epoxy sensitized) or D6 (four, with one epoxy sensitized). Ten participants were absent at both readings. Of these, four provided photographs of 2 days, either D4 and D6 or D3 and D5, and six provided a photograph on D4 (one epoxy sensitized).

Production workers were considerably younger, less often women, reported atopic dermatitis less frequently and smoking more often, had been employed for a shorter period and were less often sensitized to nonepoxy allergens of the TRUE test[®] than office workers (Table 1).

Table 1 Characteristics of participants by exposure status to epoxy components in the wind turbine industry

Characteristics	Exposure status	
	Exposed production workers (n = 180)	Nonexposed office workers (n = 41)
Age, years		
Mean (range)	34.5 (19–65)	46.8 (29–63)
Age group, n (%)		
< 30 years	70 (38.9)	1 (2.4)
30–39 years	64 (35.6)	9 (22.0)
≥ 40 years	46 (25.6)	31 (75.6)
Sex, n (%)		
Male	178 (98.9)	19 (46.3)
Female	2 (1.1)	22 (53.7)
Atopic dermatitis (self-reported), n (%)		
Yes	17 (9.4)	7 (17.1)
No	159 (88.3)	31 (75.6)
Missing	4 (2.2)	3 (7.3)
Allergic rhinitis (self-reported), n (%)		
Yes	39 (21.7)	7 (17.1)
No	137 (76.1)	31 (75.6)
Missing	4 (2.2)	3 (7.3)
Asthma (self-reported), n (%)		
Yes	25 (13.9)	6 (14.6)
No	153 (85.0)	32 (78.1)
Missing	2 (1.1)	3 (7.3)
Duration of employment, n (%)		
< 1 year	62 (34.4)	6 (14.6)
1–4 years	57 (31.7)	9 (22.0)
≥ 5 years	49 (27.2)	23 (56.1)
Missing	12 (6.7)	3 (7.3)
Smoking, n (%)		
Current	88 (48.9)	5 (12.2)
Former	44 (24.4)	11 (26.8)
Never	48 (26.7)	22 (53.7)
Missing	0 (0.0)	3 (7.3)
Sensitization to a TRUE Test [®] allergen other than epoxy resin, n (%)	15 (8.3)	9 (22.0)

In total, 16 (8.9%) of the production workers were sensitized to an epoxy component compared with none of the office workers (OR 8.3, 95% CI 0.5–141.6), with higher estimates among workers who performed filling operations (OR 14.9, 95% CI 0.9–258.8) (Table 2). The prevalence of sensitization to epoxy components decreased with increasing duration of exposed employment from 16.1% among those employed for 1 year or less to 4.1% among those employed for 2 years or more. Dermatitis affected 29 (16.1%) of the production workers and eight (20%) of the office workers (OR 0.8, 95% CI 0.3–1.8). Results that were restricted to men (Table S4; see Supporting Information) and Factory 1 (Table S5; see Supporting Information) were similar.

Table 2 Exposure to epoxy components and odds ratios (ORs) for epoxy sensitization and dermatitis in the wind turbine industry^a

Procedures and duration of epoxy exposure	Total, n	Epoxy sensitization		Dermatitis	
		n (%)	OR (95% CI)	n (%)	OR (95% CI)
Nonexposed office workers	41	0 (0)	1 (ref.)	8 (19.5)	1 (ref.)
Exposed production workers	180	16 (8.9)	8.3 (0.5–141.6)	29 (16.1)	0.8 (0.3–1.8)
Lamination	99	4 (4.0)	3.9 (0.2–74.3)	8 (8.1)	0.4 (0.1–1.0)
Filling	81	12 (14.8)	14.9 (0.9–258.8)	21 (25.9)	1.4 (0.6–3.4)
Duration of exposed employment					
None	41	0 (0)	1 (ref.)	8 (19.5)	1 (ref.)
< 1 year	62	10 (16.1)	16.6 (0.9–291.6)	16 (25.8)	1.4 (0.5–3.6)
1–2 years	57	3 (5.3)	5.3 (0.3–106.1)	5 (8.8)	0.4 (0.1–1.3)
> 2 years	49	2 (4.1)	4.4 (0.2–93.6)	6 (12.2)	0.6 (0.2–1.8)
Missing	12	1 (8.3)	–	2 (16.7)	–

CI, confidence interval; ref., reference. ^aA total of 221 participants.

Table 3 shows results stratified by atopic status and indicates no effect modification for sensitization. On the other hand, there were indications for such an effect for dermatitis because, among nonatopic workers we found an increased prevalence of dermatitis among production workers compared with office workers (OR 2.3, 95% CI 0.6–9.1), while an inverse association was seen for atopic workers (OR 0.1, 95% CI 0.0–0.5). Sensitivity analyses including only men (Table S6; see Supporting Information) and only workers from Factory 1 (Table S7; see Supporting Information) showed similar results.

Among all participants, 43.8% of sensitized workers had dermatitis and 14.6% of workers who were nonsensitized to epoxy had dermatitis (Table 4). This yields a fourfold increased odds of dermatitis (OR 4.5, 95% CI 1.6–12.7) among workers sensitized to epoxy components.

All 16 sensitized participants tested positive to work products containing both DGEBA and DGEBF, and 12 tested positive to DGEBA-R from the TRUE test[®] panel (Table 5). All 27 participants from Factory 2 and four of 13 eligible participants from Factory 1 were additionally tested with DGEBF-R from the Chemotechnique epoxy series; five participants had a concomitant reaction to DGEBF-R and two had a solitary reaction to DGEBF-R. Thus, 14 of the 16 sensitized participants were detected by the combination of the commercial tests. Furthermore, three participants had reactions to 2-phenyl glycidyl

Table 4 Epoxy sensitization and odds ratio (OR) for dermatitis among workers in the wind turbine industry

	Total, n	Dermatitis, n (%)	OR (95% confidence interval)
No epoxy sensitization	205	30 (14.6)	Reference
Epoxy sensitization	16	7 (43.8)	4.5 (1.6–12.7)

ether, 1,6-hexanediol diglycidyl ether and 1,4-butanediol diglycidyl ether. Only two participants were sensitized to a hardener product; supplemental testing did not identify the exact allergen of the product. Main constituents and CAS numbers of products causing positive patch test results are shown in Table S8 (see Supporting Information). The frequency of sensitization to additional nonepoxy allergens (benzisothiazolinone, methylisothiazolinone, formaldehyde, iodopropyl butylcarbamate and 2-n-octyl-4-isothiazolin-3-one) was low among production workers and office workers (Table S2).

Among the 21 production workers who participated in the follow-up, no new skin sensitizations to epoxy components were found, despite continued exposure for all but two participants. Two participants (10%) developed dermatitis during

Table 3 Exposure to epoxy components and odds ratios (ORs) for dermatitis and epoxy sensitization by atopic status in the wind turbine industry^a

Atopic status and exposure to epoxy components	Total, n	Epoxy sensitization		Dermatitis	
		n %	OR (95% CI)	n %	OR (95% CI)
Nonatopic (n = 190)					
Nonexposed office workers	31	0 (0)	1 (ref.)	2 (6.5)	1 (ref.)
Exposed production workers	159	13 (8.2)	5.8 (0.3–100.2)	26 (16.4)	2.3 (0.6–9.1)
Atopic (n = 24)					
Nonexposed office workers	7	0 (0)	1 (ref.)	6 (85.7)	1 (ref.)
Exposed production workers	17	3 (17.7)	3.6 (0.2–79.7)	3 (17.7)	0.1 (0.0–0.5)

CI, confidence interval; ref., reference. ^aInformation on atopic dermatitis was missing for seven participants.

Table 5 Positive patch test results by product and allergen test material in the wind turbine industry at day (D)4 and D6^a

Test material	Case number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Epoxy resin TRUE test [®]	-/-	+/+	+/+	+/+	++/++	+/+	+/+	+/÷	+/+	+/+	-/-	+/+	+/+	-/-	+/+	-/-
Product ^b																
Resin no. 1	+/+	+/+	+/+	+/+	++/++	+/+	+/+	+/÷	+/+	+/+	+/+	++/++	+/+	NT	NT	NT
Resin no. 2	+/+	+/+	+/+	+/+	++/++	+/+	++/++	+/÷	+/+	++/++	+/+	+/+	+/+	NT	NT	NT
Resin no. 3	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	+/+	+/+	+/+
Resin no. 4	+/+	+/+	+/+	+/+	++/++	+/+	+/+	+/÷	+/+	+/+	+/+	+/+	+/+	+/+	+/+	+/+
Resin no. 5	+/+	+/+	+/+	+/+	++/++	+/+	+/+	+/÷	+/+	+/+	+/+	+/+	+/+	NT	NT	NT
Resin no. 6	+/+	+/+	+/+	+/+	++/++	-/+	+/+	+/÷	+/+	+/+	+/+	+/+	+/+	NT	NT	NT
Resin no. 7	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	+/+	+/+	-/-
Hardener no. 1	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
Hardener no. 2	-/-	-/-	-/-	-/-	+/+	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	NT	NT	NT
Hardener no. 3	-/-	-/-	-/-	-/-	+/+	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	NT	NT	NT
Specific epoxy allergens																
Epoxy resin, Bisphenol F	NT	NT	NT	NT	NT	÷/++	++/÷	NT	÷/++	NT	NT	NT	++/++	++/++	+/+	+/+
2-Phenyl glycidyl ether	NT	NT	NT	NT	NT	÷/++	++/÷	NT	÷/++	NT	NT	NT	++/++	NT	NT	NT
1,6-Hexanediol diglycidyl ether	NT	NT	NT	NT	NT	+/÷	++/÷	NT	-/-	NT	NT	NT	+/+	NT	NT	NT
1,4-Butanediol diglycidyl ether	NT	NT	NT	NT	NT	+/÷	++/÷	NT	-/-	NT	NT	NT	+/+	-/-	-/-	-/-

^aOnly products and components resulting in positive reactions are shown. ^bProduct names are confidential and are not to be disclosed. +, ++, +++, positive; -, negative; ÷, doubtful reaction; ÷, no reading; NT, not tested. Patch test reaction at D4 and D6 are separated by a solidus.

the 2-year follow-up period; neither were sensitized to epoxy components. One worker who tested positive at baseline retested positive at follow-up.

Discussion

In this study, we found that almost 9% of the production workers were sensitized to an epoxy component compared with none in the control group, and that sensitization occurred most frequently among workers with less than 1 year of exposure and among the most highly exposed workers who performed filling operations. Among nonatopic workers, a higher risk of dermatitis was suggested for those exposed to epoxy components compared with those who were nonexposed, whereas the opposite was seen for atopic workers. Sensitization was associated with dermatitis that affected about 40% of the sensitized workers. All sensitized workers were sensitized to DGEBA-R and DGEBF-R. Four of 16 participants who had a reaction to epoxy components used at the factories, did not react to the epoxy resin of the TRUE test[®] panel. Two of those who tested negative were also tested with the Chemotechnique epoxy series and showed a positive test result. The remaining two sensitized participants were not tested with specific epoxy allergens including DGEBF-R.

The prevalence of sensitization to DGEBA-R has been reported to vary from 0.2% to 0.5% in the general population, and up to 1.3% in patients with dermatitis.^{9,10,26} The prevalence of DGEBA-R sensitization among exposed workers in our study (8.9%) is similar to the prevalence among production workers of the 2004 Danish wind turbine industry study (10.5%).^{6,7} However, these two studies are not directly comparable as the 2004 study recruited production workers with dermatitis, whereas in the present study we recruited production workers with expected high risk of exposure regardless of any dermatitis.

The majority of production workers sensitized to epoxy had been employed for less than 1 year, which is in accordance with former studies and indicates a short latency period of sensitization and a healthy worker effect.^{15,26} The low sensitivity of the TRUE test[®], which missed one-quarter of the epoxy-sensitized participants, emphasizes the importance of tailored testing.^{6,27–29}

One strength of this study is the inclusion of a control group of workers who were not exposed to epoxy components and were examined according to the same protocol as the exposed workers. All participants were tested with a tailored test series including the epoxy products handled at the workplaces. Two readings were performed 4 and 6 days after the application of the test material as recommended by the guidelines from the European Society of Contact Dermatitis.¹⁹ None of the participants in the control group reacted to epoxy components, indicating that false positive reactions were unlikely. All patch test applications and readings were performed by the same experienced biomedical laboratory technician, which eliminated interexaminer variation. The appearance of dermatitis can fluctuate and therefore we included self-

reported and clinically verified dermatitis in our case category. For all participants, information was provided about duration of exposed employment, work procedures, and amount of epoxy used, which made it possible to localize the potential risk factors at work.

This is a cross-sectional study with well-known limitations with respect to temporality between exposure and outcome. Other limitations include the low participation rate, especially among the controls, and skewed distribution of age and sex between the exposed workers and the control group, which precluded adjustment. However, sensitivity analyses of male participants showed only similar results.

Individuals with dermatitis (with no further specification) or sensitization to epoxy components are not allowed to work with epoxy products according to national worker protection legislation, whereas there are no such restrictions for office workers. Office workers are able to continue work in the presence of dermatitis, whereas production workers with dermatitis may leave employment, be transferred to nonexposed jobs or have their employment terminated as required by the legislation, leaving healthier workers in the production area. The higher prevalence of atopic dermatitis and more frequent positive patch test results to nonepoxy allergens of the TRUE test[®] among office workers compared with production workers are in line with healthy worker selection for those who are exposed and those who are nonexposed at the two factories, and furthermore this is expected to confound results towards the null. Therefore, we expect that we have underestimated the true impact of epoxy exposure on sensitization and dermatitis in this industry. The decreased risk of dermatitis observed for atopic workers is also indicative of selection dependent on the presence of dermatitis. Therefore, we emphasize the positive association between exposure and dermatitis suggested for the nonatopic workers.

Study participation was voluntary and may also have depended on the presence of dermatitis among exposed workers and nonexposed workers, and may have biased results in any direction. Owing to rotating shifts and absence from work, some patch test readings relied on photoassessments, but this number was small and we do not believe that this affected our results substantially.³⁰

Participants were selected for this study because of their manual lamination and finishing work tasks with expected high risk of skin exposure to epoxy components. Findings are expected to reflect the risk of sensitization and dermatitis for similar work tasks, but not production work in general in the wind turbine industry.

Another limitation of this study is that we did not systematically examine participants for facial dermatitis, which is a common manifestation owing to airborne exposure to epoxy resin components in sensitized people.^{31–33} This could have led to an underestimation of the prevalence of dermatitis. The study includes a limited number of workers especially in the control group, and all estimates are provided with considerable uncertainty as illustrated by the wide CIs.

In conclusion, we studied workers with high risk of skin exposure to epoxy components. The participants worked at factories with well-established and highly prioritized health and safety policies; however, these measures did not sufficiently protect them from sensitization. A possible explanation is that epoxy resin components are often translucent, leaving skin contamination unrecognized. Adding a fluorescent tracer will make resins visible and may improve the awareness of inexpensive procedures and behaviour.^{34–42} Replacing current epoxy resin systems with new systems that have comparable technical properties but less skin sensitizing capacity is another novel and promising way forward to reduce the risk of skin exposure and sensitization.^{43,44} Furthermore, one in four sensitized workers did not react to the epoxy resin of a baseline test panel, which emphasizes the importance of tailored testing.

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Conflicts of interest

The authors declare no conflicts of interest. Siemens Gamesa Renewable Energy financially supported a total of 50 patch tests. Siemens Gamesa Renewable Energy and Vestas Wind Systems A/S supported the study by providing test locations and access to the company as well as helping with organizational challenges associated with the study. The companies had no role in study design and data collection, and were not involved in data analysis, interpretation and conclusions. Only the authors had access to the data in this study and they take complete responsibility for the integrity of the data and the accuracy of the data analysis.

Ethics statement

The Regional Ethical Committee has approved the study (1-10-72-52-18).

Data availability

Data available on request owing to privacy/ethical restrictions.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Table S1 Specific epoxy allergens from Chemotechnique Diagnostics tested on participants from Factory 1 with a positive patch test to epoxy.

Table S2 Additional nonepoxy allergens and patch test reactivity among exposed and nonexposed workers in the wind turbine industry.

Table S3 Invited and participating study population from the wind turbine industry.

Table S4 Exposure to epoxy components and odds ratios for epoxy sensitization and dermatitis in the wind turbine industry, men only.

Table S5 Exposure to epoxy components and odds ratios for epoxy sensitization and dermatitis in the wind turbine industry, Factory 2 participants excluded.

Table S6 Exposure to epoxy components and odds ratios for dermatitis and epoxy sensitization by atopic status in the wind turbine industry, men only.

Table S7 Exposure to epoxy components and odds ratios for dermatitis and epoxy sensitization by atopy status in the wind turbine industry, Factory 2 participants excluded.

Table S8 Main chemical constituents and Chemical Abstracts Service numbers of test materials causing positive patch test results in the wind turbine industry.

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