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Exposure to Flour Dust in South African Supermarket Bakeries: Modeling of Baseline Measurements of an Intervention Study

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Introduction: Exposure to flour dust has been reported as an important risk factor for allergic respiratory disease among bakery workers. A high prevalence of allergic sensitization and asthma was recently reported in South African supermarket bakeries. The aim of this study was to conduct a detailed exposure assessment of these bakeries so as to provide the baseline for a broader intervention study.

Methods: A total of 211 full-shift personal samples were collected on randomly selected individuals within five different job categories in 18 bakeries. The samples were analyzed for particulate mass and specific flour dust allergens (wheat, rye, and fungal alpha-amylase). Exposure models were developed using job, bakery size, tasks, and specific ingredients used. Bakery and worker were regarded as random effect components.

Results: Bread bakers had the highest average (geometric mean) exposures (1.33 mg m^{-3} flour dust particulate, 13.66 μg m^{-3} wheat allergens, and 5.14 μg m^{-3} rye allergens). For alpha-amylase allergens, most samples were below the limit of detection for several occupational titles. In the mixed effect models, the significant predictors of elevated exposure to inhalable dust particulate as well as wheat and rye allergen concentrations were large bakery size, bread baking, and use of cereal flours, while tasks such as confectionery work were negatively correlated with these exposure metrics. Weighing tasks and use of premix products were associated with increased exposure to fungal alpha-amylase. A high correlation between particulate dust and wheat ($r = 0.84$) as well as rye ($r = 0.86$) was observed, with a much lower correlation between particulate dust and fungal alpha-amylase ($r = 0.33$). Overall, a low proportion (39%) of bakery stores implemented various control measures to reduce dust exposures in the bakeries.

Conclusions: This study confirms that current exposure control strategies in supermarket bakery stores are inadequate in reducing dust exposures to protect the health of bakery workers.

Keywords: allergen; bakery; exposure assessment; exposure modeling; flour; fungal alpha-amylase; rye; wheat

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INTRODUCTION

Baker's asthma due to flour dust exposure in the work environment is one of the most commonly reported manifestations of occupational asthma in both industrialized and rapidly industrializing countries (Jeebhay and Quirce, 2007). Recent studies of the development of small- and medium-sized bakeries in South Africa over the past decade have demonstrated a dramatic rise in franchise (in-store) bakeries from 20% in 1995 to 44% in 2002. This has resulted in an increasing number of workers potentially at risk of developing baker's allergy and asthma. In a recent study of supermarket bakery workers, at least a quarter of workers were sensitized to cereal flour allergens and 13% has baker's asthma (Baatjies *et al.*, 2009). A fatal case of baker's asthma in a bakery assistant from a South African supermarket bakery has also been reported (Ehrlich, 1994).

Although exposure to inhalable dust, wheat, and fungal alpha-amylase allergens among workers in industrial, traditional, and supermarket bakeries is very well documented in several European and North American countries (Brant *et al.*, 2005; Elms *et al.*, 2005, 2006; Meijster *et al.*, 2009), no exposure data are available for bakeries in general and supermarkets in particular for rapidly industrializing countries, such as South Africa. Exposure data from studies in large industrial bakeries and traditional bakeries demonstrate that workers at the front end of the baking process (dough makers, bread formers, and bread bakers) have the highest average dust exposures (average inhalable dust exposures of 3–6 mg m^{-3}) (Burdorf *et al.*, 1994; Nieuwenhuijsen *et al.*, 1994; Houba *et al.*, 1997). Furthermore, results from the only published study of bakeries in UK supermarkets showed that the mean (geometric) dust exposure concentrations for bakers were on average 1.2 mg m^{-3} (Brant *et al.*, 2005). Other more recent studies conducted in the UK also demonstrated that mixers/weighers/sievers had the highest median total dust and fungal alpha-amylase levels and suggesting that aside from job category, bakery size was also an important determinant of elevated exposure to flour dust allergens (Elms *et al.*, 2003a, 2005, 2006). These studies concluded that changes in the site of production of bread products from large scale industrial to small scale supermarket bakeries with the consequent burden of disease were important targets for proactive interventions aimed at reducing dust levels. It has been suggested that the use of appropriate knowledge and effective dust control measures, coupled with training and supervision, can substantially reduce flour dust exposure levels in bakeries. A sound evidence base for effective interventions in bakeries is currently lacking. Meijster *et al.* (2008) have recently evaluated the potential of different control measures to reduce peak exposures. They concluded that more rigorous interventions than reduction measures nowadays regularly applied are needed to bring down exposure sufficiently (Meijster *et al.*, 2008, 2009).

This study is part of a larger intervention study entailing both exposure assessment and health outcome components. The study described in this paper aimed at assessing personal inhalable exposure to flour dust, wheat and rye allergens, and fungal alpha-amylase allergens in bakeries of a large supermarket chain store. Furthermore, an inventory of control measures currently used in these bakeries was also conducted. The results from the study will provide a baseline estimate of exposure and establish the basis for the intervention strategy to be implemented. The second major aim was to develop predictive exposure models based on the identified exposure determinants in the bakeries. It is envisaged that these models will be used to generate exposure predictions for individual participating in the health study to enable a more detailed study of exposure–response relationships for clinically relevant endpoints observed (Baatjies *et al.*, 2009).

METHODS

Study population

The study population consisted of workers from 18 bakeries from a large supermarket chain store in South Africa. Supermarket bakeries had an average workforce of 20 workers per bakery (range: 6–42) with an average production output of ~10 000 bakery units per week per bakery (range: 4360–18 346). Bakeries were stratified into small, medium, and large size based on the number of workers employed and the production output (bread, rolls, and cakes) of the bakery. The bakery size indices were derived using tertile values of the following variables as cut-off points—number of employees: ≤14, 15–21, and >21; and production output in units per week: ≤7504, 7505–10 868, and >10868. An equal number of bakeries were randomly selected from each stratum. Within each bakery, five main job titles could be distinguished: bread baker, bakery supervisor, bakery manager, confectioner, and counterhand (Table 1). From these selected bakeries, 109 workers (21%) were selected for sampling, while at the same time ensuring that all five job titles were adequately represented in each bakery. Using this sampling frame, all workers selected agreed to participate in the study.

Table 1. Description of jobs within supermarket bakeries in relation to main activities performed

Job title	Description
Bread baker	Mainly involved in tasks such as dough making; bread and roll production, which involves emptying bags of flour and other ingredients such as enzymes into a mixer; and weighing of ingredients, dusting of steel tables, and bread and rolls with flour.
Confectioner	Mainly involved with the baking and finishing (decorating) of cakes and pastries, including weighing of ingredients, preparing pastry dough, and operating dough processors.
Supervisor	Perform several tasks, including placing orders, supervising production, and frequently perform some tasks assigned to bakers.
Manager	Perform similar tasks to that of supervisors as well as training of workers, customer care, and frequently perform tasks of confectioners.
Counterhand	Serving customers, adequate stocking of the counter, and wrapping of products purchased by customers.

Walk through survey

Raw product inventory Prior to conducting the environmental sampling, an inventory of all ingredients used in all the bakeries was undertaken. Bulk samples of raw products were collected in sterile 50 ml Greiner centrifuge tubes and sent to Research Institute for Occupational Medicine (BGFA), in Germany, for analysis. The main aim of this inventory was to determine whether enzymes (fungal alpha-amylase and xylanase) were present in the flours and more specifically in the premixes used in these bakeries. The results were also to be used for identifying the panel of allergen extracts to be used for skin prick testing and allergen-specific IgE levels in the sera of workers in the epidemiological study.

Assessment of control measures A structured walk-through survey of all bakeries was also used to obtain detailed information with regard to work tasks, raw products used, and specific control measures implemented in relation to flour dust exposures in each bakery. The checklist included questions on the following parameters identified at each supermarket store: presence and type of ventilation system, use of personal protective equipment (3 M, FFP2 respirators), education and training activities, number of mixing tubs in each bakery, work practices during dough preparation (shaking of bags, enclosed mixing tubs, and use of oil versus flour for dough processing), and cleaning methods used in each bakery. Workers were observed throughout the shift and detailed information on tasks performed and specific work practices were recorded during personal environmental sampling. This process contributed towards the systematic prioritization of intervention measures and their subsequent evaluation in the next phase of the project.

Personal sampling measurements

Personal environmental sampling was performed on all selected study subjects on two consecutive days. Full-shift samples were obtained on each participating worker using a PAS6 sampling head connected to a Gillian GilAir pump with constant-flow calibrated at $2\ \mathrm{l\,min^{-1}}$. Teflon filters (Millipore; pore size 1.0 μm, 25 mm diameter) mounted in the sampling head were used to collect the dust. Field blanks were included for each sampling day. Filters were weighed before and after sampling using a microbalance (Mettler Toledo AG245). Filters were acclimatized prior to weighing for 24 h in a room with controlled humidity (45%) and temperature (21°C) to ensure standard weighing conditions. The limit of detection (LOD) for the flour dust was 0.08 mg, calculated using the average weight difference of the blank filters plus three times the standard deviation. None of the samples collected had values below the LOD for total dust particulate.

Allergen concentration determination

After weighing for total dust particulate, the samples were prepared for immunological quantification by delaminating the filters and directly extracting them in 2.5 ml phosphate-buffer saline with 0.05% Tween-20, centrifuging 15 min at 1000 g, and storing the supernatant at −20°C (Bogdanovic *et al.*, 2006a). Wheat flour allergen concentrations were determined using an enzyme-linked immunosorbent assay inhibition technique with rabbit anti-wheat IgG4, and for samples below the detection limit, the sandwich enzyme immunoassay was used, as previously described (Bogdanovic *et al.*, 2006b). Fungal alpha-amylase allergens were measured using a sandwich enzyme immunoassay with monoclonal mouse antibodies for capture and affinity-purified polyclonal rabbit IgG antibodies for detection as described in Sander *et al.* (2007) and by Bogdanovic *et al.* (2006c).

Rye flour allergens were measured using a rabbit (NewZealand White) immunized with an allergenic rye seed extract (Sander *et al.*, 2005) and a two-sited assay developed after Protein G purification of the coating antibodies and antigen affinity purification and biotinylation of the detection antibodies. Polymeric peroxidase-conjugated streptavidin (SA-poly-HRP80, RDI, Flanders, NJ, USA) and 2,2′-azino-bis(3-ethylbenzthiazoline-6-sulphonic acid (Sigma, Taufkirchen, Germany) as a substrate were used for measurement. Sample concentrations were read by interpolation of optical density values (OD_{414} nm) on a four-parameter dose–response curve of the standard preparation, using Softmax Pro 4.7.1 from Molecular Devices (Sunnyvale, CA, USA). The assay was able to measure rye protein in a concentration range of 0.21–9.5 ng ml^{-1}. Each filter sample extract was measured in a dilution series of three 2-fold dilutions (first dilution at least 1:2). The mean coefficient of variation of these filter sample extract measurements was 7.8%.

Statistical analyses

All statistical analyses were performed using STATA version 8 and SAS version 9.1 (SAS 2002). Descriptive statistics were calculated stratified by job title. PROC UNIVARIATE procedure in SAS was used to explore the distribution of the exposure data. All exposure data followed a skewed distribution, requiring the exposure data to be log transformed prior to statistical analysis. Mixed effects models were used to evaluate the association between exposure to inhalable dust, wheat, rye, and fungal alpha-amylase allergens and covariates (e.g. job title, supermarket store size, tasks, and products), taking into account worker and supermarket store as random effects. PROC MIXED from SAS System Software Version 9.1 (SAS, 2002) was used for this analysis. We assumed a compound symmetry structure of the correlation matrix that any two repeated measurements of the same worker have equal correlation irrespective of the time interval between them. Mixed effects models were applied with and without the fixed effects to estimate the explained variance of the models produced. Variance components were estimated using the Restricted Maximum Likelihood method. Stepwise model building procedure was used to develop predictive models for inhalable dust, wheat, rye, and fungal alpha-amylase allergen concentrations with the final model only including covariates that were significant at the 10% level. Model improvement (increase in explained variance) was tested using the difference in −2-log likelihood ratio between the two models. If no additional variability was explained by adding more variables, expansion of the model was stopped. The percentage of the between-worker variance explained by the full model in comparison to the empty models were calculated as follows: between-worker variance = $[(S^2_{bw}$ empty model $- S^2_{bw}$ full model$)/S^2_{bw}$ empty model$] \times 100$.

RESULTS

Walk-through survey, product inventory, and control measures

The inventory of control measures in bakeries in most situations revealed a very low presence of control measures to reduce exposure to flour dust (Table 2). None of the bakeries made use of local exhaust ventilation; dough mixing tubs were not covered with lids resulting in dust becoming airborne during the dough mixing process, and vacuum cleaners were not used during cleaning operations. Furthermore, only 39% of bakery managers interviewed provided specific health and safety information to their workers on the precautions to reduce exposure to flour dust. Results of flour dust levels stratified by presence of control measures demonstrated no differences in average exposure levels when using process and behavioral control measures (divider oil, personal protective equipment, and training) (data not shown). However, structural controls such as physically separating departments were associated with markedly reduced levels of fungal alpha-amylase (0.30 versus 0.17 ng m^{-3}, Wilcoxon rank-sum test $P = 0.125$).

Table 2. Uptake of control measures evaluated during walk-through survey of supermarket bakeries

Control measures	Uptake (%) ($n = 31$)
Structural/engineering controls	
Departments physically separated	2 (6)
Local exhaust ventilation system	0 (0)
Closure of mixing tubs:	
Partially closed	0 (0)
Totally closed	0 (0)
Process controls	
Use of divider oil instead of flour on dough table	1 (3)
Use of vacuum for cleaning	0 (0)
Surveillance of flour dust levels	0 (0)
Personal protective equipment	
Supply of appropriate personal respiratory protective equipment	11 (35)
Guidance on use of personal protective equipment	10 (32)
Information and training activities	
Information and training on flour dust	12 (39)

Analysis of bulk samples (two rye flour, eight wheat flour, and 16 premix products) for enzymes showed very low fungal alpha-amylase concentrations (0.75–100 ng mg^{-1}) in seven premix products and two rye products and was undetectable in remaining products. Xylanase levels were much lower (<0.5 ng ml^{-1}) and were only detected in a small proportion (3 of 16) of premixes and both rye flour products.

Personal exposure levels

A total of 211 full-shift personal samples were collected. Of the 109 workers sampled, 7 (6%) had one measurement and 102 (94%) had two repeated measurements. Bread bakers had the highest average flour dust particulate concentration [geometric mean (GM): 1.33 mg m^{-3}], double the exposure of confectioners and bakery supervisors, while the exposure of counterhands was half that of confectioners (GM: 0.28 mg m^{-3}; Table 3). With respect to the distribution of wheat allergen levels, bakers (GM: 13.66 µg m^{-3}) had twice as high exposures as confectioners (GM: 5.82 µg m^{-3}) and confectioners five times higher than counterhands. Although similar patterns in levels of exposure in the different jobs were observed for rye allergen concentrations, these concentrations were generally half that of wheat allergen. The GM fungal alpha-amylase levels were relatively low (GM: 0.29 ng m^{-3}), with very minimal variation in exposure levels across the job categories and most samples (81%) being below the LOD.

Correlation analysis

A very strong correlation was observed between log-transformed inhalable dust particulate concentration and log-transformed wheat (Pearson r = 0.84, $P < 0.001$) and rye allergen concentrations (Pearson r = 0.86, $P < 0.001$) as well as between wheat and rye allergen concentrations (Pearson r = 0.98, $P < 0.001$; Fig. 1). However, the degree of correlation between inhalable dust and fungal alpha-amylase was much lower (Pearson r = 0.33, $P < 0.001$).

Mixed effects models

The results from the mixed effects models are presented in Table 4. The results reveal that significant predictors of elevated exposure to inhalable dust particulate, wheat, and rye allergen were job title, use of specific ingredients (flour), and working in a large bakery, while certain tasks such as confectionery work was negatively correlated with the exposure

Table 3. Personal inhalable particulate, wheat, rye, and fungal alpha-amylase allergens concentration levels in supermarket bakeries according to job title

Job title	k	n	Inhalable dust (mg m^{-3})				Wheat allergen (µg m^{-3})				Rye allergen (µg m^{-3})				Fungal alpha-amylase (ng m^{-3})			
			AM	GM	GSD	Range	AM	GM	GSD	Range	AM	GM	GSD	Range	AM	GM	GSD	Range
Bread baker	57	112	1.83	1.33	2.25	0.25–7.29	20.67	13.66	2.66	1.79–69.65	8.24	5.14	2.89	0.30–31.08	0.38	0.15	2.32	LOD–19.62
Confectioner	19	38	0.85	0.65	2.08	0.11–3.33	7.81	5.82	2.25	0.82–30.68	2.98	2.04	2.41	0.24–12.96	0.29	0.12	2.14	LOD–6.54
Baker supervisor	7	13	0.72	0.56	2.05	0.20–2.67	6.18	4.99	1.93	2.28–17.79	2.16	1.74	1.97	0.61–6.84	0.10	0.10	1.17	LOD–1.17
Bakery manager	7	13	0.72	0.51	2.34	0.12–2.48	7.93	3.41	4.01	0.32–40.28	2.52	1.99	4.06	0.09–9.32	0.14	0.12	1.58	LOD–0.51
Counterhand	19	35	0.35	0.28	1.89	0.11–1.96	2.80	1.16	4.81	0.002–29.86	0.98	0.39	4.57	LOD–10.92	0.12	0.11	1.40	LOD–0.64
Overall	109	211	1.27	0.81	2.61	0.11–7.29	13.71	6.71	4.09	0.002–69.65	5.36	2.42	4.30	LOD–31.08	0.29	0.13	2.08	LOD–19.62

AM: Arithmetic mean; GSD: geometric standard deviation; k: number of workers sampled in an exposure group; n: number of measurements in a group; LOD wheat: 0.001 µg m^{-3}; LOD rye: 0.001 µg m^{-3}; LOD fungal alpha-amylase: 0.083 ng m^{-3}; number of measurements below LOD wheat: 0; rye: 1 (0.5%); fungal alpha-amylase: 169 (80%).

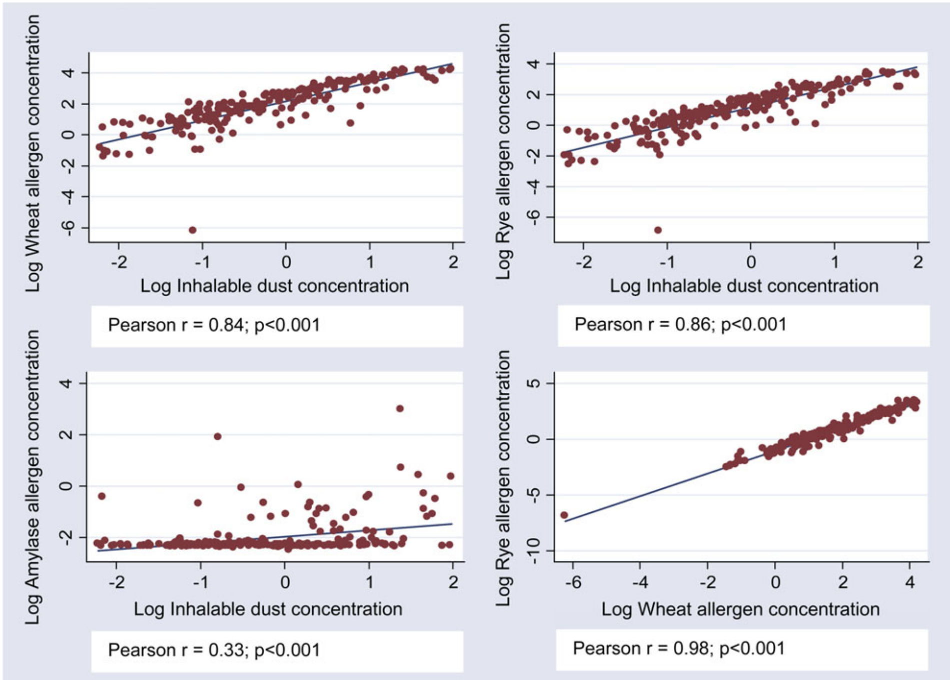

Fig. 1. Relationship between inhalable dust (ln mg m^{-3}), wheat (ln μg m^{-3}), rye (ln μg m^{-3}), and fungal alpha-amylase (ln ng m^{-3}) allergen concentration in supermarket bakeries: (n = 211).

Table 4. Estimates for variables in final mixed effects multivariate model of the log-transformed exposure to inhalable dust particulate and allergens (wheat, rye, and fungal alpha-amylase) in supermarket bakeries

Model variables (fixed effects)		Inhalable dust particulate		Wheat allergen		Rye allergen		Fungal alpha-amylase	
		β	*P*-value	β	*P*-value	β	*P*-value	β	*P*-value
Intercept[a]		−1.53	<0.001	−0.13	0.555	−1.26	<0.001	−2.21	<0.001
Job[b]	Bread baker	1.56	<0.001	2.54	<0.001	3.05	<0.001	—	
	Manager	1.33	<0.001	2.48	<0.001	3.04	<0.001	—	
	Confectioner	1.17	0.001	2.22	<0.001	2.80	<0.001	—	
	Supervisor	0.99	0.002	1.78	<0.001	2.20	<0.001	—	
Bakery[c]	Large store	0.36	0.003	0.39	0.018	0.44	0.010	—	
Tasks	Confectionery	−0.58	0.001	−1.01	<0.001	−1.28	<0.001	—	—
	Weighing ingredients	[d]	—	—	—	—	—	0.21	0.057
Ingredients	Flour use	0.27	0.091	0.37	0.084	—	—	—	—
	Premix product use	—	—	—	—	—	—	0.02	0.010
Var_bw (CI)[e]		0.19 (0.08–0.30)		0.28 (0.07–0.48)		0.36 (0.14–0.58)[f]			
Var_ww (CI)[g]		0.30 (0.23–0.41)		0.69 (0.53–0.93)		0.67 (0.52–0.90)		0.45 (0.37–0.56)	
Var_bb (CI)[h]		[f]		[f]		[f]		0.04 (0.02–0.28)	

[a]The intercept gives the exposure level working as a counterhand in a small bakery without performing any of the tasks specified in the model and absence of flour use.
[b]Job as counterhand is the reference group.
[c]Small bakeries are the reference group.
[d]Fixed effect not significant in final model.
[e]Variance component between workers [confidence interval (CI)].
[f]Random effect not significant in model.
[g]Variance component within workers (CI).
[h]Variance component between bakeries (CI).

metrics. On the other hand, weighing tasks and use of premix products were associated with increased exposure to fungal alpha-amylase. Variability in exposure among supermarket bakery workers was moderately (40–52%) explained by models of flour dust particulate, wheat, and rye allergens and poor (8%) for fungal alpha-amylase (Table 4). A large component of the between-worker differences for dust particulate, wheat, and rye allergens were explained by the final models (71–80%; Table 5). The within subject (worker) variability was significant in all models for dust particulate, wheat, and rye allergens. The supermarket store random effect was significant only for fungal alpha-amylase, with 7% of the between bakery variability explained by the final model.

DISCUSSION

The results from this study demonstrate that bakers have the highest mean inhalable flour dust particulate, wheat, rye, and fungal alpha-amylase levels compared to other job titles. In the mixed effect models, job title, bakery size, and use of cereal flours were associated with significantly increased exposures, while tasks such as confectionery with decreased exposures. This is the first study to our knowledge documenting exposure to inhalable flour dust particulate and particularly wheat, rye, and fungal alpha-amylase allergens in the Southern African context and only one of the two studies conducted in supermarket bakeries globally. The findings will provide detailed baseline measurements for the intervention study currently being conducted.

Table 5. Variance components and confidence intervals (95% CI) of the log-transformed exposure to inhalable dust particulate and allergens (wheat, rye, and fungal alpha-amylase) in supermarket bakeries

Exposure variable	Exposure determinants	Between-worker variance	95% CI	Within-worker variance	95% CI	Reduction in between worker variance[a]
Dust	None	0.65	0.43–0.88	0.29	0.22–0.39	0
	Job	0.30	0.17–0.44	0.29	0.23–0.39	54
	Bakery size	0.62	0.41–0.84	0.29	0.22–0.39	5
	Tasks	0.64	0.42–0.86	0.29	0.23–0.39	3
	Ingredients	0.35	0.20–0.51	0.33	0.25–0.45	46
	Job + task	0.24	0.12–0.36	0.29	0.23–0.40	63
	Job + task + bakery size	0.21	0.10–0.32	0.29	0.23–0.39	68
	Job + task + bakery size + ingredients	0.19	0.08–0.30	0.30	0.23–0.41	71
Wheat	None	1.35	0.87–1.82	0.67	0.52–0.91	0
	Job	0.52	0.27–0.78	0.67	0.52–0.90	61
	Bakery size	1.33	0.86–1.80	0.67	0.52–0.91	1
	Tasks	1.33	0.86–1.80	0.68	0.52–0.91	2
	Ingredients	0.65	0.34–0.96	0.74	0.57–1.01	52
	Job + task	0.34	0.12–0.55	0.68	0.52–0.91	75
	Job + task + bakery size	0.31	0.10–0.52	0.67	0.52–0.90	77
	Job + task + bakery size + ingredients	0.28	0.07–0.48	0.69	0.53–0.93	80
Rye	None	1.52	1.00–2.04	0.67	0.52–0.91	0
	Job	0.62	0.33–0.90	0.67	0.52–0.90	60
	Bakery size	1.49	0.98–2.00	0.67	0.52–0.90	2
	Tasks	1.49	0.98–2.00	0.67	0.52–0.91	2
	Job + task	0.39	0.16–0.62	0.67	0.52–0.91	74
	Job + task + bakery size	0.36	0.14–0.57	0.67	0.52–0.90	77
Fungal alpha-amylase	None	0.05	0.12–0.31	0.49	0.40–0.60	0
	Tasks	0.05	0.02–0.28	0.46	0.38–0.57	−2
	Ingredients	0.04	0.02–0.29	0.46	0.38–0.56	8
	Task + ingredients	0.04	0.02–0.28	0.45	0.37–0.56	7

[a]Between-worker variance = [(S^2_{bw} empty model−S^2_{bw} full model)/S^2_{bw} empty model] × 100.

The mean inhalable dust particulate exposures of this group of supermarket bakery workers were lower than the levels reported by Bulat *et al.* (2004), Elms *et al.* (2005), and Meijster *et al.* (2007, 2009) among workers in industrial (1.0–4.7 mg m^{-3}) and traditional bakeries (1.11–2.10 mg m^{-3}) but comparable to levels reported by Brant *et al.* (2005) (0.5–1.2 mg m^{-3}) in a study of supermarket bakery workers in the UK (Brant *et al.*, 2005; Elms *et al.*, 2005; Meijster *et al.*, 2007, 2009). However, the GM wheat allergen exposures (6.71 μg m^{-3}) were comparable to recent studies in traditional bakeries (7.4 μg m^{-3}) but higher than levels observed in industrial bakeries (3.6 μg m^{-3}) (Meijster *et al.*, 2007). The mean fungal alpha-amylase levels were similar across most jobs in our study, most samples (81%) being below the LOD, and levels were generally much lower than levels reported by other studies (0.40–1.7 μg m^{-3}) (Elms *et al.*, 2006; Meijster *et al.*, 2007, 2009). These differences in enzyme levels were also observed in the analysis of bulk samples of products obtained from the bakeries under study, which demonstrated very low levels of fungal alpha-amylase, when compared to Dutch bakeries that generally contained much higher levels (Bogdanovic *et al.*, 2006). The results of the allergen exposure levels underscore the high prevalence of sensitization to wheat (26%) and rye (24%) flour when compared to the markedly low levels of sensitization to fungal alpha-amylase (4%) observed in the epidemiological study of workers employed in these bakeries (Baatjies *et al.*, 2009). Interestingly, although the mean dust exposure levels in the current study were similar to those reported by Brant *et al.* (2005) in UK bakeries (GM: 0.5 mg m^{-3}), the prevalence of sensitization to wheat was much lower (11%) in the latter study. It is unlikely that the atopy or smoking status of the subjects has played a major role as the prevalence of atopy in both study population was similar (41 versus 42%). Although the prevalence of smoking was higher in the South African study (47 versus 33%), it would appear that smoking does not have significant adjuvant effects in flour dust- (wheat, fungal alpha-amylase) exposed workers (Nielsen *et al.*, 2005).

While exposure to wheat and fungal alpha-amylase allergens among bakery workers has been well described, exposure to rye flour allergens has not been previously documented, and little is known about allergenic role of rye flour in baker's asthma. This is the first study to document occupational exposure to rye allergens among supermarket bakery workers as rye flour is increasingly being used in bread baking. An increasing number of studies, mainly case reports, have recently reported rye flour allergens as an important cause of baker's asthma (Bensefa *et al.*, 2004; Ehrlich and Prescott, 2005; Letran *et al.*, 2008). Among these is a report of baker's asthma from a supermarket chain store of our study population, highlighting a greater clinical response to rye than wheat flour. These studies highlight a potentially emerging role of rye flour allergens in baker's asthma that merits further investigation.

In the mixed model analysis, aside from job status as a bread baker, large bakery size, specific tasks, and ingredients use were significant determinants of exposure. This is consistent with other studies, demonstrating bakery size, job, and tasks as significant predictors of dust particulate and wheat allergen exposures (Elms *et al.*, 2005; Peretz *et al.*, 2005). This observation is borne out in the epidemiological study that found that among those workers sensitized to wheat, 43% of workers worked in large bakeries (63 of 146), when compared to 24% working in small bakeries (35 of 146). An additional observation in our study was the use of premixed flour products that was significantly associated with higher levels of fungal alpha-amylase exposure. This finding is in agreement with previous studies suggesting that fungal alpha-amylase exposure is highly dependent on the mix of ingredients and the concentration of fungal alpha-amylase used (Meijster *et al.*, 2007). The bulk sample analysis in our study also demonstrated relatively higher fungal alpha-amylase concentrations (0.75–100 ng mg^{-1}) in premixed products compared to other raw products used. However, the concentration of xylanase was much lower (<0.5 ng ml^{-1}) and unlikely to be a major determinant of symptoms. Elms *et al.* (2003) have also shown that enzymes such as xylanase, cellulose, and hemicellulase cause sensitization in only 6% of bakery workers.

The exposure models developed for flour dust particulate and wheat allergen levels performed better in explaining total variability (48–52%) in exposure in this study of supermarket bakery workers when compared to Dutch traditional bakers (27–39%) (Meijster *et al.*, 2007). This may be explained in part by the fact that in the Dutch studies, different types of bakeries were included, whereas in the current study, the type of bakeries were similar, resulting in less exposure variability since the between-company differences are small (low contrast). However, studies by Burstyn *et al.* (1997, 1998) were able to explain up to 79% of total dust exposure variability since the investigators took into consideration various other determinants such as frequency and time spent on activities, which appeared to be an important source of day-to-day exposure variability.

Overall, exposure models in this study explained a significant proportion of between-worker variability for inhalable dust particulate and wheat and rye allergens (71–80%), which is comparable to the upper limit of the range of 56–78% reported by Peretz *et al.* (2005). However, the explained between-worker variability for fungal alpha-amylase was much lower (7%) and similar to a recent study in Dutch bakers explaining only 9% of the total exposure variability (Meijster *et al.*, 2007). This may in part be attributable to the low levels of fungal alpha-amylase found in bulk product samples obtained from these bakeries and the absence of a concentration gradient for fungal alpha-amylase across the various job titles in these bakeries.

The findings of this current study suggest that the measurement of inhalable flour dust particulate in personal samples may be a good surrogate of exposure to wheat and rye allergens due to the high correlation ($r = 0.84$–0.86) observed between these two parameters of exposure. This is an important factor to bear in mind with regard to hygiene monitoring, especially in resource-poor settings with limited access to advanced immunological assays. This information maybe useful in measuring dust particulate levels when evaluating the impact of specific interventions to comply with legislative requirements. However, the degree of correlation between inhalable dust particulate and fungal alpha-amylase was much lower ($r = 0.33$), indicating that this does not hold for fungal alpha-amylase (Burstyn *et al.*, 1999).

In this study, an inventory of control measures in bakeries revealed a paucity of adequate measures (poor local exhaust ventilation systems, uncovered dough mixer tubs, and absence of vacuum cleaners) to reduce exposure to flour dust in most bakeries. However, the impact of structural controls was evident in that physically separate departments was associated a 2-fold decrease in the fungal alpha-amylase exposures. This demonstrates that exposure to fungal alpha-amylase can be greatly reduced particularly among confectioners and workers not involved in bread baking by physically separating these processes in a bakery. Other studies evaluating the effectiveness of interventions in bakeries are limited. Burstyn *et al.* (1997) showed that the substitution of dusting with the use of divider oil in bread production was associated with lower exposures. Elms study in the UK found that although half of the bakeries were thought to have adequate control measures in place, activities such as dry sweeping and flour dusting by hand were common practices. The study concluded that knowledge of good working practices was limited and that with appropriate knowledge and use of good control practices, training, and supervision, exposure levels could be reduced (Elms *et al.*, 2005). Similarly, in the Netherlands, a lack of control measures to reduce exposure to flour dust was also observed in the flour sectors evaluated, and when control measures were present, their use was limited (Meijster *et al.*, 2007). Recently, a study investigating the long-term changes in flour dust exposure from 1985 to 2003 demonstrated that there was no significant downward temporal trend in flour dust exposures, despite initiatives to control dust exposure in bakeries (van Tongeren *et al.*, 2009). The study suggests that active involvement and commitment of government and industry is fundamental to reducing dust levels and the disease burden associated with high flour dust levels.

In conclusion, this study being the first exposure assessment undertaken in South Africa will provide an important baseline estimate of exposure in supermarket bakeries. The exposure models developed can now be used to generate exposure predictions for individual workers investigated during the baseline health study in order to study dose–response relationships for clinically relevant endpoints in baker's allergy. Despite the overwhelming evidence that workplace exposures to flour dust should be controlled, current prevention strategies in bakeries appear not to be very satisfactory. The intervention strategy of the larger study in South African supermarkets will be aimed at focusing interventions specifically linked to sources of high-risk exposures observed in this study. In this way, the detailed information gathered with regard to current control measures or lack thereof will be used to optimize the intervention strategy currently being implemented in these supermarket bakeries.

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