

# Development, validation and testing of a skin sampling method for assessment of metal exposure

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## Summary

**Background.** Nickel, cobalt and chromium are frequent skin sensitizers. Skin exposure results in eczema in sensitized individuals, the risk being related to the skin dose.

**Objectives.** To develop a self-sampling method for quantification of skin exposure to metals, to validate the method, and to assess its feasibility.

**Methods.** Defined metal doses (0.01–5 µg) were applied to the fingers of 5 participants. Skin areas (2 cm<sup>2</sup>) were sampled with 1% HNO<sub>3</sub>, either as 0.1 ml on a swab, or as 0.5 ml on a wipe. Furthermore, 17 participants performed self-sampling by swab after 2 h of leisure activity. Samples were extracted in 1% HNO<sub>3</sub> and analysed by inductively coupled plasma mass spectrometry.

**Results.** The sampling efficiency by swab was 46%, as compared with 93% for acid wipe sampling, for all tested doses. Most metal from the skin dose was detected in the first swab (33–43%). Despite lower sampling efficiency by swab, skin doses of metals following 2 h of leisure activity without hand washing were quantified in all participants, and ranged from 0.0016 to 0.15 µg/cm<sup>2</sup>, from 0.00014 to –0.0020 µg/cm<sup>2</sup> and from 0.00048 to –0.027 µg/cm<sup>2</sup> for nickel, cobalt, and chromium, respectively.

**Conclusions.** The results indicate a future potential of skin sampling by swab to detect and monitor metals on skin by self-sampling. This will contribute to better knowledge of metal skin exposure among dermatitis patients, workers, and the general population.

**Key words:** acid wipe sampling; chromium; cobalt; metal skin dose; nickel; risk assessment; skin exposure.

Nickel (Ni), cobalt (Co) and chromium (Cr) are common metal skin sensitizers, and contact allergy is frequent in the general population. A recent study in five European countries showed prevalences of contact allergy to Ni, Co

and Cr, respectively, of 14.5%, 2.2% and 0.8% at the population level (1). Contact allergy to metals is also common in the younger population. Recent prevalence data show that Ni (8%) is the most common skin sensitizer in Swedish adolescents, and allergy to Co (1%) and Cr (0.3%) is also observed (2).

Once a person is sensitized, allergic contact dermatitis resulting from skin exposure to the allergen may develop. The risk is related to the metal skin dose, that is, the amount of metal deposited on the skin. The threshold skin dose required to elicit allergic contact dermatitis is usually much lower than the threshold level for sensitization, and varies between individuals (3). It has been shown that the threshold skin doses for elicitation of an allergic reaction by a patch test in 10% of sensitized individuals (ED<sub>10</sub>)

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are  $0.78 \mu\text{g}/\text{cm}^2$  for Ni (4),  $0.063\text{--}1.95$  for Co (5), and  $0.44 \mu\text{g}/\text{cm}^2$  for Cr (3). The duration and frequency of contact are also important determinants of skin exposure to metals. The contribution from many short and frequent contacts with metallic items, adding to a total (daily) skin dose, has recently been shown (6). However, neither the quantity of such a skin dose nor its relevance to contact allergy and dermatitis is fully understood.

To assess and quantify metals on skin, different sampling strategies can be used (such as removal techniques or *in situ* measurements), with consideration of their respective qualities and limitations. The acid wipe sampling method is one common removal technique for quantification of metals on the skin surface (7). The method of using a wipe moistened with 1%  $\text{HNO}_3$  for skin cleaning was developed by Berglund et al. with the purpose of preventing contamination from the skin during collection of blood samples from young children (8). The acid wipe proved to be efficient in removing metals from the skin surface, and caused no harm to the skin, so the cleaning concept was adopted into a sampling method for metals on skin (7). Since the acid wipe sampling method was introduced, it has been used in several studies on skin deposition of metals in occupational settings (9–11) and in experimental skin exposure studies (12–14). The procedure of wipe extraction, which is a practical part of the sample preparation prior to analysis, has, in some studies, been modified to allow the detection of low metal skin doses (6).

Methods for quantification of metals on skin have brought understanding of skin exposure to metals; in particular, occupational exposures have been investigated (9–11). Some contribution to a daily, total metal skin dose from leisure activities, as shown for a gym workout, is expected but has rarely been studied (15). One possible reason is the practical difficulty in monitoring the diverse contacts from various leisure activities. Nevertheless, much can be learnt from broader investigations of daily skin exposure to metals. This would be facilitated by a simple and efficient method for skin sampling.

Therefore, our study aims were (i) to develop a self-sampling method for quantification of metal skin doses, (ii) to compare the efficiency of the self-sampling method with that of acid wipe sampling, and (iii) to assess the feasibility of self-sampling for assessment of metal skin exposure.

## Materials and Methods

Healthy volunteers participated in the method development experiments ( $n = 5$ ) or in the assessment of feasibility of the self-sampling ( $n = 17$ ). The inclusion criteria

were (i) no history of Ni, Co or Cr allergy and (ii) no current hand dermatitis. The KI Nord ethics committee at the Karolinska Hospital, Stockholm granted ethical approval (DNR 03-492). All participants gave informed consent before taking part in the study.

Diluted nitric acid (1%  $\text{HNO}_3$ ) was prepared from deionized water ( $16.8 \text{ M}\Omega/\text{cm}$ ) and 65%  $\text{HNO}_3$  (Merck, Darmstadt, Germany). Mixed standard solutions containing 0 (blank vehicle), 0.5, 5, 50 and 250 mg/l Ni, Co and Cr in 1%  $\text{HNO}_3$  and 99.5% ethanol (1:1) were prepared from 1000 mg/l stock solutions (Teknolab, Kungsbacka, Sweden) for application of known metal doses to the skin. All materials used for the experiments were acid-washed (10%  $\text{HNO}_3$  for 24 h, rinsed four times in deionized water, and dried in the laboratory), unless otherwise stated.

### The efficiency of skin sampling by swab and wipe

Before the application of defined metal doses to the fingertips, participants washed their hands with soap and water, and dried them with paper towels. Thereafter, the operator rinsed the participant's hands with 1%  $\text{HNO}_3$  and deionized water, and dried them again with a paper towel. The skin sampling areas on the volar tips of the thumbs, index fingers, middle fingers, and ring fingers, as well as the control fingers (little fingers), on both hands of the 5 volunteers were marked by indicating the corners of a  $2\text{-cm}^2$  area.

By use of a micropipette (Transferpette; BRAND, Wertheim, Germany),  $20 \mu\text{l}$  of each standard concentration [0 (blank vehicle), 0.5, 5, 50 and 250 mg/l] was applied to the marked areas on fingertips defining metal skin doses of 0, 0.01, 0.1, 1 and  $5 \mu\text{g}/2 \text{ cm}^2$  Ni, Co, and Cr, respectively (Fig. 1a). We dosed one hand at a time, performing sampling when hands were dry (5–10 min), before dosing on and sampling from the other hand.

Skin areas on the right hand were sampled with acid wipes, and areas on the left hand were sampled with cotton swabs (Fig. 1b,c). The skin areas on the right thumb, index finger, middle finger, ring finger and little finger were wiped (for 30 seconds each). Three consecutive cellulose tissues (injection wipes; Paper-Pak, Sundbyberg, Sweden), moistened with 0.5 ml of 1%  $\text{HNO}_3$  by use of a micropipette, were used for each area. The wipes were placed in individual test tubes (25 ml; Sarstedt, Nümbrecht, Germany) for metal extraction.

On the left hand, skin areas on the thumb, index finger, middle finger, ring finger and little finger were sampled by rubbing (for 30 seconds) with three consecutive cotton swabs (Critical Swab™ double cotton tip, paper handle, 76.2 mm; VWR International, Radnor, PA, USA). Each swab was moistened with 0.1 ml of 1%  $\text{HNO}_3$ , already

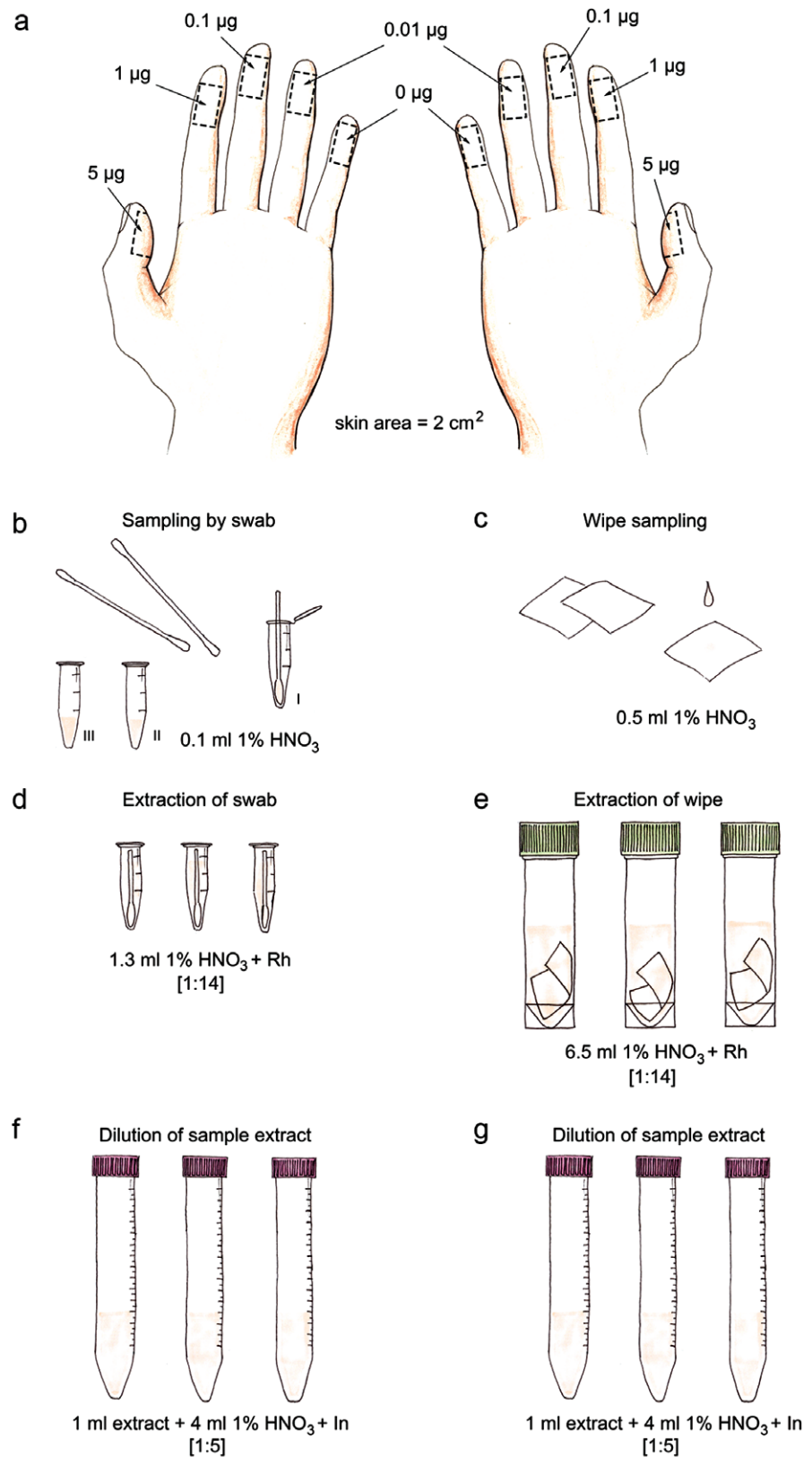


**Fig. 1.** Schematic overview of the experimental steps in the test of sampling efficiency with two different skin sampling methods: sampling by swab and wipe sampling. Metal skin doses were applied on  $2 \text{ cm}^2$ -areas on the fingertips (a). Areas on the left hand were sampled by three consecutive swabs (b) and areas on the right hand were sampled with three consecutive wipes (c). Extraction of metal from swabs (d) and wipes (e) was made in 1%  $\text{HNO}_3$ . Rh was added to monitor the extraction efficiency. The sample extracts were diluted with 1%  $\text{HNO}_3$  and In was added as internal standard prior to chemical analysis (f, g).

pipetted into Eppendorf tubes® (Sarstedt) in order to facilitate the sampling. The acid volume (0.1 ml) was chosen on the basis of a pilot test. After sampling, the swab was placed in the same Eppendorf tube® that previously contained the acid.

Blank samples with wipes/swabs and acid and with acid only were prepared in triplicate.

#### Self-sampling with swabs for assessment of metal skin exposure

To test the feasibility of the simplified skin sampling method for assessment of metal skin exposure, 17 participants were equipped with cotton swabs and Eppendorf tubes® prepared with 0.1 ml of 1% HNO<sub>3</sub>. The participants were instructed to wash their hands with soap and water, and then, after ~2 h of leisure activity without hand washing, to sample from their skin surface.

In order to simplify the procedure, only one cotton swab was used for sampling of each skin area. The participants received a written and illustrated description of the sampling procedure, explaining that ~2 cm<sup>2</sup> on the volar tips of the thumb and index finger of the non-dominant hand should be sampled. In these instructions, a 2-cm<sup>2</sup> surface was drawn to facilitate understanding of how large such a surface is. After self-sampling, it was recommended to wash the hands with soap and water to remove any traces of the diluted acid from the skin. Participants returned the used swabs, placed in marked Eppendorf tubes®, and provided a short description of the type of activity preceding sampling (Table S1).

#### Metal extraction

Metals from wipe and swab samples were extracted in 1% HNO<sub>3</sub>. To monitor the efficiency of extraction, rhodium (Rh) was added. The acid was pipetted into test tubes with wipes (6.5 ml) and Eppendorf tubes® with swabs (1.3 ml) (Fig. 1d,e). The extraction volumes were selected to keep a constant ratio between the sampling volume and the extraction volume in the two cases (1:14). Blank samples were treated in the same way as the samples.

To extract the metal, the test tubes containing wipe samples were placed on an orbital shaker (200 rpm) for 45 min, and Eppendorf tubes® with swabs were left on the table for ~2 h. Thereafter, 1 ml of the extract solution was transferred from each of the test tubes/Eppendorf tubes® with a micropipette, into new Falcon™ test tubes (15 ml; VWR International). An additional 4 ml of 1% HNO<sub>3</sub> was added to each tube (Fig. 1f,g). The diluted sample extracts were stored at room temperature until chemical analysis.

#### Chemical analysis

Inductively coupled plasma mass spectrometry (iCAP Q; Thermo Scientific, Waltham, MA, USA) was used for analysis of Ni, Co, Cr and Rh concentrations in sample extracts. Indium (In) was used as an internal standard, and added to all samples and calibration solutions at a concentration of 5 µg/l. Isotopes <sup>58</sup>Ni, <sup>60</sup>Ni, <sup>52</sup>Cr, <sup>53</sup>Cr, <sup>59</sup>Co, <sup>103</sup>Rh and <sup>115</sup>In were analysed in the kinetic energy discrimination mode with triplicate readings of each sample.

Calibration standard and blank solutions were diluted from stock solutions of Ni, Co, Cr and Rh (1000 mg/l; Teknolab) in 1% HNO<sub>3</sub>. Concentrations of 0 (blank), 0.1, 1, 5, 10, 50, 100 and 500 µg/l were used for calibration, and recalibration was performed if the recovery of the internal standard was <80% or >120%. Quality control samples were run every 10 samples, and showed stable concentrations that did not vary by more than 10%. The results of measured concentrations were corrected for the internal standard recovery in the individual samples. The method limits of detection are shown in Table S2.

#### Results

Acid wipe sampling was adopted into a simplified method using a cotton wool swab for sampling of the skin. The skin dose ranges of Ni, Co and Cr were selected to correspond to similar studies and to represent relevant levels of occupational exposure (6, 7, 14, 16).

Finally, skin sampling by swab was used by 17 participants to test the feasibility of self-sampling, and to quantify metal skin doses from various leisure activities.

#### The efficiency of skin sampling by swab and wipe

Measured skin doses (Table S3) were compared with the doses applied to skin for evaluation of sampling recovery. The average recoveries of metal skin doses measured in 5 participants using skin sampling by swab or wipe are shown in Table 1.

The sampling efficiency obtained with three consecutive swabs was 40–54%, and that obtained with wipe sampling was in the range of 64–100%. The sampling efficiency of wipe sampling was similar to previous reported values for this method (6, 7, 17). Sampling efficiency for the specific elements (based on all four doses) did not deviate considerably when skin sampling was performed with the swab: 47% for Ni, 47% for Co, and 44% for Cr. Hence, the average amount of metal, namely 46%, can be considered to be the overall sampling efficiency of this method. The average recovery of the wipe sampling method (three consecutive wipes) was 93%. However,

**Table 1.** Average sampling efficiency for metal skin doses applied to the fingertips in 5 participants; results are based on skin sampling with three consecutive swabs or wipes<sup>a</sup>

| Metal applied to skin <sup>b</sup> ( $\mu\text{g}/2\text{ cm}^2$ ) | Sampling efficiency for Ni (%), mean $\pm$ SD |              | Sampling efficiency for Co (%), mean $\pm$ SD |             | Sampling efficiency for Cr (%), mean $\pm$ SD |              |
|--------------------------------------------------------------------|-----------------------------------------------|--------------|-----------------------------------------------|-------------|-----------------------------------------------|--------------|
|                                                                    | Swab                                          | Wipe         | Swab                                          | Wipe        | Swab                                          | Wipe         |
| 5                                                                  | 54 $\pm$ 3 <sup>c</sup>                       | 87 $\pm$ 11  | 54 $\pm$ 3 <sup>c</sup>                       | 85 $\pm$ 11 | 53 $\pm$ 4 <sup>c</sup>                       | 85 $\pm$ 12  |
| 1                                                                  | 45 $\pm$ 12                                   | 101 $\pm$ 10 | 44 $\pm$ 11                                   | 98 $\pm$ 9  | 40 $\pm$ 11                                   | 98 $\pm$ 10  |
| 0.1                                                                | 44 $\pm$ 3                                    | 98 $\pm$ 11  | 44 $\pm$ 3                                    | 101 $\pm$ 8 | 40 $\pm$ 3                                    | 100 $\pm$ 13 |
| 0.01                                                               | 46 $\pm$ 10                                   | 64 $\pm$ 37  | 46 $\pm$ 6                                    | 102 $\pm$ 8 | 44 $\pm$ 5                                    | 98 $\pm$ 34  |

<sup>a</sup>Sampling volume of 1% HNO<sub>3</sub> was 0.5 ml for the wipe and 0.1 ml for the swab. SD, standard deviation.

<sup>b</sup>Twenty microlitres of the standard solutions containing Ni, Co and Cr at concentrations of 0 (blank vehicle), 0.5, 5, 50 and 250 mg/l, corresponding to the amounts of 0, 0.01, 0.1, 1 and 5  $\mu\text{g}/2\text{ cm}^2$  of Ni, Co and Cr applied to 2 cm<sup>2</sup>-marked areas of the thumbs, index fingers, middle fingers, ring fingers and little fingers of both hands of the participants. Results from control areas (little fingers dosed with vehicle) were used for background correction unless the quantified dose of control sample was below the limits of detection.

<sup>c</sup>Recovery data from the thumb (5  $\mu\text{g}$ ) were, in 1 case, not included for calculation of the average method recovery, because the applied dose was slightly outside the marked area, and hence the full applied dose was not sampled.

slightly lower recovery of Ni (87%) than of Co (96%) and Cr (95%) was observed.

In Fig. 2, the average amounts (%) of Ni, Co and Cr skin doses in 5 participants are compared for the individual first, second and third swabs and wipes. The results show that 33–43% of the deposited metal skin dose was sampled by the first swab, and 63–79% was sampled by the first wipe, respectively. The average sampling efficiency of the different skin doses with a single swab was 36% (37%, 38% and 35% for Ni, Co and Cr, respectively). The corresponding recovery for a single wipe was 69% (67% of Ni, 73% of Co, and 71% of Cr) (Fig. 2).

The measured individual efficiencies of wipe sampling and sampling with a swab both showed the highest recovery rate for the higher skin dose (5  $\mu\text{g}/\text{cm}^2$ ) and lower recovery with lower skin doses. In general, the sampling efficiency was higher with a wipe than with a swab.

#### Self-sampling with a swab for assessment of metal skin exposure

The skin sampling method was tested for self-use by 17 participants who sampled from skin on the thumb and index finger of the non-dominant hand after 2 h of leisure activity. One swab per surface, moistened with 0.1 ml of 1% HNO<sub>3</sub>, was used for the assessment of metals on skin. The measured skin doses of Ni, Co and Cr ( $\mu\text{g}/\text{cm}^2$ ) are shown in Fig. 3.

The measured amounts of metals (30–40% recovery of deposited skin doses) on the thumbs and index fingers of all participants were 0.002–0.154  $\mu\text{g}/\text{cm}^2$  for Ni, <0.001–0.002 for Co, and <0.001–0.027 for Cr. Among the various leisure activities performed by the 17 participants for 2 h, the highest measured skin dose of Ni (0.154  $\mu\text{g}/\text{cm}^2$ ) was detected on the thumb after

installing light sources (H, Table S4). The highest doses of Cr (0.027  $\mu\text{g}/\text{cm}^2$ ) and Co (0.0020  $\mu\text{g}/\text{cm}^2$ ) were found on the fingers of the participant riding a bus and shopping in a hardware store (A, Table S4). Also, weekly grocery shopping in a supermarket resulted in relatively high metal skin doses in 1 case (N, Table S4).

#### Discussion

In the present study, we have introduced a skin sampling method that was adapted for self-sampling based on the concept of acid wipe sampling. The efficiency of sampling metals from the applied skin doses ( $\mu\text{g}/\text{cm}^2$ ) by using three consecutive swabs (46%) was lower than that with the acid wipe sampling method (93%). In both cases, most metal was detected in the first swab (33–43%) or wipe (63–79%). Despite this lower sampling efficiency by swabs, we were able to quantify skin doses of Ni, Co and/or Cr in all participants ( $n = 17$ ) after 2 h of leisure activity without hand washing.

When a higher sampling efficiency is desirable, for example when skin doses are expected to be low or close to the limit of detection, we would suggest some further modification of the sampling procedure. As the lower sampling efficiency of swab sampling than of acid wipe sampling may be related to the smaller volume of 1% HNO<sub>3</sub> used for moistening of the swab than of the wipe, the use of a swab that can hold a larger volume of liquid would be of interest for further evaluation. The sampling efficiency observed in this study is rather constant, within the entire dose range tested (30–40%). This finding reflects the fact that the risk of 'overloading' or saturating the used swab by metal upon sampling is limited; hence, the 0.1-mL volume of 1% HNO<sub>3</sub> is not the cause of limited sampling efficiency. Also, the extraction procedure was evaluated

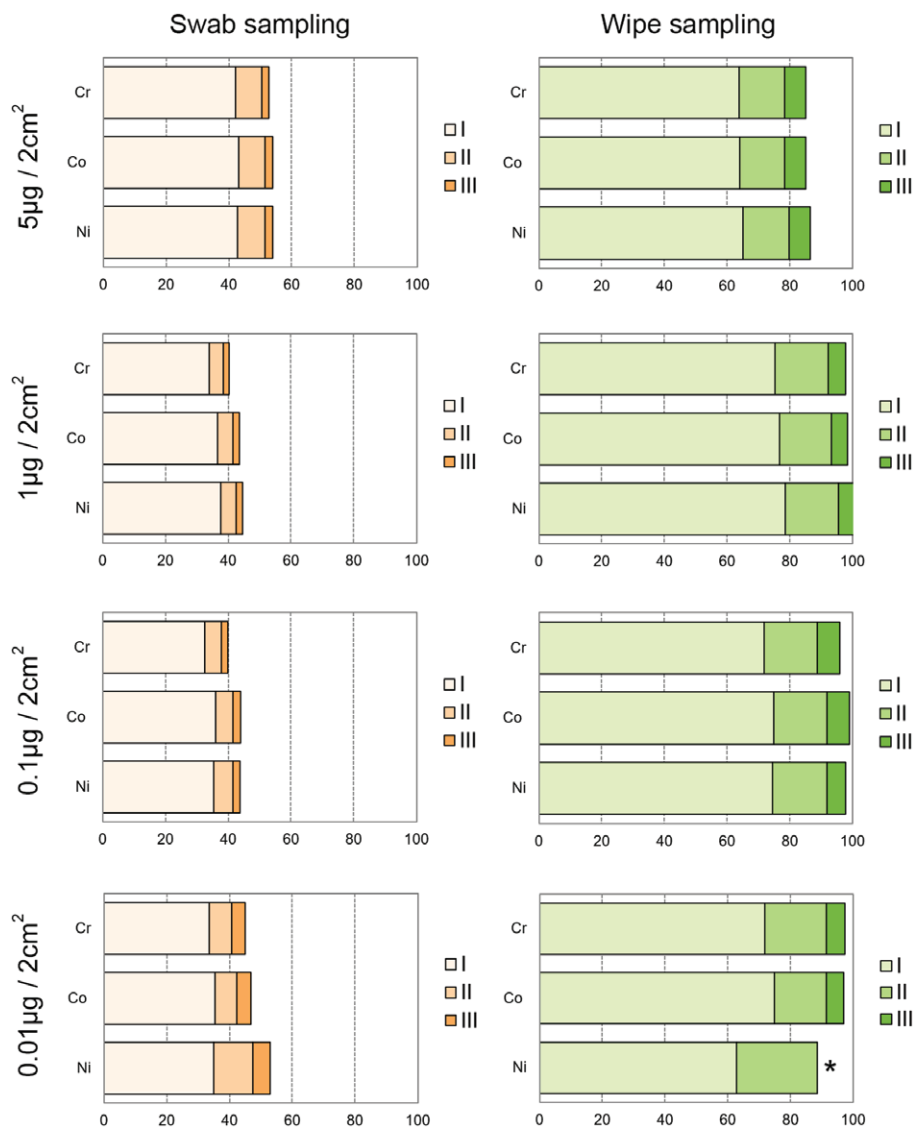


**Fig. 2.** Comparison of average sampling efficiencies (%) for Ni, Co and Cr by concomitant swab sampling and wipe sampling from hands with 1% HNO<sub>3</sub> in 5 participants. Results for swab sampling are shown in the left column and wipe sampling results in the right column for the applied metal doses (5, 1, 0.1, 0.01 µg/2 cm<sup>2</sup>). The amounts of metal detected in the first (I), second (II) and third (III) consecutive swabs or wipes are displayed in the graphs. \*No Ni was detected in the third wipes.

in order to rule out potentially insufficient extraction of swabs; we could verify 80–112% recovery of Rh added as an internal standard to the extraction solution. This implies that, basically, no metal from the extraction fluid is lost by absorption into the swab. However, it is not known whether the cottonwool swab material itself can retain metals to a higher degree than the cellulose wipe.

Studies of skin exposure to metals, particularly those in occupational settings, often involve the collection of different samples by staff. This is time-consuming work and therefore costly. In situations where it is not practically feasible for an operator to perform the skin sampling, a self-sampling method can provide the possibility of assessing skin exposure to metals. This is shown herein by the results regarding metal skin dose in 17 participants who

successfully performed self-sampling after 2 h of leisure activity. The sampling kit, including swabs and the defined volume of 1% HNO<sub>3</sub> pre-packed in individual Eppendorf tubes® together with sampling instructions, can easily be prepared and provided to study participants or patients. Even though the work-up of the samples requires some effort in the laboratory performing metal analysis, the advantage of this self-sampling method lies in the possibility of monitoring snapshot levels of skin exposure to metals.

The results from the assessment of metals on skin after 2 h of leisure activity showed that all participants had quantifiable amounts of metal (Ni) on their skin. Ni was, with a few exceptions, present in larger amounts than Co and Cr (Table S4). The snapshot levels of metal skin doses

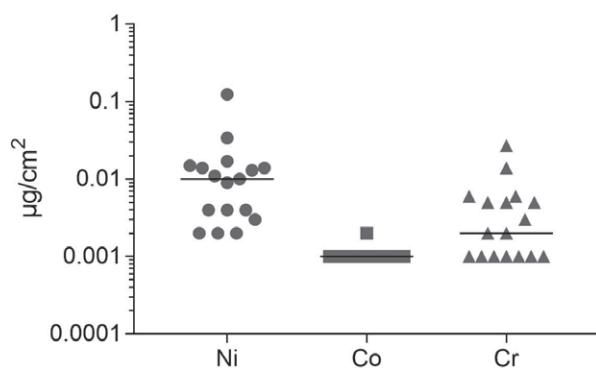


**Fig. 3.** Skin doses measured by self-sampling with a single swab for assessment of metals on skin after 2 h of leisure activity. The results show individual skin doses ( $\mu\text{g}/\text{cm}^2$ ) on the non-dominant thumb and index fingers and median skin doses (as lines) for Ni, Co, and Cr. Participants ( $n = 17$ ) washed their hands with soap and water 2 h before sampling their skin. No hand washing was allowed during the subsequent 2 h of leisure activity. Each participant sampled approximately  $2\text{-cm}^2$  skin surfaces of the volar tips of the thumb and index fingers on the non-dominant hand by using a single swab per surface, moistened with  $0.1\text{ ml}$  of  $1\%$   $\text{HNO}_3$  from an Eppendorf tube®. The skin area was rubbed with the swab for 30 seconds. The skin doses from leisure activity can be regarded as snapshot measures, and do not account for possible background metal already present on skin.

can, in some cases, illustrate similar skin doses as for some occupational studies of metals on skin, despite yielding only  $\sim 40\%$  of the actual metal dose. As experience with this method is still limited, we would like to stress that these data cannot yet be used for further interpretation or comparisons with other studies of skin doses. They may now serve primarily as results for method development, pointing at a future potential to detect metals by self-sampling from skin surfaces by swab.

The evaluation of metal skin doses from leisure activity with our chosen sampling strategy implied that no information on the start condition was available, but the assumption was made that the skin was clean after a hand wash with soap and water before the 2-h period. This could have been verified by including skin sampling directly after the hand wash. However, we aimed to test the method in a relevant context and to measure snapshot skin doses of metals in order to mainly explore the feasibility of self-sampling for detection of metals on skin.

Generally, knowledge about skin exposure to metals among consumers from daily contact with materials, surfaces, items and products is very limited. One reason may be that this type of exposure has not been regarded of interest, even though consumers, and not only workers, use coins, tools, handles and many other items that deposit Ni onto the skin (9). However, new

insights into the metal skin doses resulting from short and frequent skin contact with metals (6) indicate that consumer skin exposure should also be monitored. A recent study in gyms showed that a 1-h workout using Ni-releasing equipment such as weight machines and dumbbells can result in deposition of considerable doses of Ni on the skin (15). The extent of such skin exposure and its potential contribution to the development of contact allergy and dermatitis are presently mostly unknown. We suggest that the self-sampling method, after further experience, will provide a useful tool for easy assessment of skin doses in future studies of daily occupational and consumer exposure to sensitizing metals.

## Conclusions

In this study, we have developed, validated and tested a method for simplified quantification of metals on skin by self-sampling with a single swab. This approach is considered to be an alternative when the metal skin dose is of interest but wipe sampling performed by an operator is not practically feasible.

The sampling efficiency was lower for swab sampling than for wipe sampling, independently of the dose within the tested skin dose range. Most metal was detected in the first swab (33–43%) or wipe (63–79%); more metal was detected by three consecutive swabs (46%) or three consecutive wipes (93%). Despite this lower sampling efficiency with swabs, we were able to quantify skin doses of metal in all participants by self-sampling after 2 h of leisure activity.

With this successful, although limited, experience, we conclude that the results indicate a future potential for detecting and monitoring metals on skin by self-sampling. This can provide better knowledge regarding skin exposure to metals in a broader context, including occupational and leisure activity, as well as the possibility of characterizing metal skin exposure in sensitized patients.

## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Table S1.** Measured skin doses of Ni, Co and Cr in participants ( $n = 17$ ) following 2 h of leisure activity<sup>a</sup> without hand washing.

**Table S2.** Limits of detection (LOD) ( $\mu\text{l}/\text{l}$ ) from the chemical analysis of samples from recovery tests and assessment of skin metal skin exposure from leisure activity For Ni, Co, and Cr, the LOD is represented as a dose ( $\mu\text{g}/\text{cm}^2$ ) corresponding to the lowest level of metals detected in samples.

**Table S3.** The average amounts of Ni, Co and Cr recovered from defined skin doses applied in 5 participants, sampling skin with swab or wipe.

**Table S4.** Average sampling efficiency of the first swabs that were used for sampling different skin doses of Ni, Co and Cr applied to the fingertips of 5 participants.

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