# Bioavailability of Soil-adsorbed Cadmium in Orally Exposed Male Rats

***Pauline A.E.L. Schilderman, Edwin J.C. Moonen, Pascal Kempkers, and Jos C.S. Kleinjans***

Department of Health Risk Analysis and Toxicology, Maastricht University, Maastricht, The Netherlands

During the last few decades, the industrial production and use of Cd resulted in the release of significant quantities of Cd into the environment. Concern about health risks of human exposure to this toxic metal, which may be contained in soil and other environmental compartments, has increased significantly in recent years. Soil ingestion is a potentially important pathway of exposure to soil-adsorbed environmental contaminants, especially for young children exhibiting hand-to-mouth behavior. Health risk assessments are usually based on unchanged bioavailability of soil-adsorbed pollutants, e.g., heavy metals, neglecting interactions of metals with the soil matrix, which may lead to relatively lower bioavailability. This study was conducted to determine the bioavailability of Cd adsorbed to soil in rats. Eight-week-old male Lewis rats were given either a soil polluted with $CdCl_2$ (150 μg Cd/rat) dissolved in 5% gum acacia or an equal amount of Cd as $CdCl_2$ dissolved in saline. Control rats were gavaged with isotonic saline. Cd concentrations in liver, kidney, brain, heart, and blood, as well as Cd content of urine and feces were analyzed using graphite furnace atomic absorption spectrometry. Tissue Cd concentrations in soil-treated animals were significantly lower than the tissue concentrations in the Cd-saline group; in the liver and kidneys of the Cd-saline and Cd-soil groups, 4 and 2.7% respectively, of the original doses were recovered. Relative bioavailability, calculated on the basis of blood Cd levels for the Cd-soil group as compared to the Cd-saline group, appeared to be 43%. No differences in the excretion pattern of Cd into feces were observed between the Cd-saline and Cd-soil groups. After 6 days, over 91% of the original dose was recovered in the feces of both Cd-treated groups. Cd excretion via urine was very low, but in the Cd-soil group a significant increase in urinary Cd was observed as compared to the control group. However, the amount of Cd excreted into urine of the Cd-soil group during the experimental period corresponded to only 0.01% of the original dose. In the Cd-saline group, no additional Cd was excreted into urine as compared to the control group. These results indicate that the soil matrix significantly reduced the absorption of Cd in the gastrointestinal tract. Consequently, exposure assessment models, assuming an unaffected bioavailability of soil-adsorbed Cd, overestimate the internal dose and thereby overestimate health risks associated with direct ingestion of soil particles. *Key words*: adsorption, bioavailability, cadmium, pollutants, soil. *Environ Health Perspect* 105:234–238 (1997)

Environmental contamination by Cadmium has increased enormously in the last few decades as a result of its increased industrial use, its presence in agricultural fertilizers, and the disposal of wastes containing Cd (*1–4*). Estimates show that the worldwide anthropogenic emissions of Cd exceed contributions from natural sources (terrestrial, marine, volcanic, biogenic) by a factor close to 10 (*5*).

Cd is a highly toxic metal, which after absorption, accumulates in the human body (mainly in liver and kidney) because of its long biological half-life (*6,7*). The main toxic effects resulting from chronic exposure to Cd are tubular dysfunction and disturbances in calcium homeostasis and bone metabolism (*8*). In rodents Cd is classified as a potent carcinogen, capable of inducing a variety of tumors. In humans Cd is considered to be a suspect carcinogen for the lung, the kidney, and possibly the prostate (*6,8,9*).

Soils contaminated by environmental toxicants such as Cd constitute a potential risk for human health. Human exposure to contaminants in soil may occur through the inhalation of dust derived from soil at a contaminated site, through dermal absorption of contaminated soil, by direct ingestion of soil and dust particles due to the hand-to-mouth pathway, or by secondary exposure through food chain routes in which initial ingestion uptake occurred in animals and agricultural crops used for food production (*10–12*). A significant route of exposure to soil-adsorbed environmental pollutants is soil ingestion (*13,14*). Although incidental soil ingestion can occur at all ages, significant soil ingestion primarily occurs between the ages of 2 and 6 years (*15,16*). The representative intake of soil and dust particles via the hands by children has been reported to range from 10 to 200 mg/day (*8*); however, ingestion up to 1200 mg soil/day has also been reported (*17*). For adults ingestion values of 0–10 mg/day seem reasonable (*14*).

Evaluation of health risks associated to toxic agents has been based mainly on results of studies with pure chemicals. However, physical and chemical parameters of soil such as particle size, percent clay, and percent organic matter may significantly affect the degree to which pollutants are adsorbed to soil and, consequently, the bioavailability of the contaminant (*18*). Since soil particles are not likely to be absorbed in the gastrointestinal tract, adsorption to the soil matrix may relatively decrease the endogenous dose; on the other hand, gastric acidity will affect the adsorption strength to the soil matrix. Consequently, differences may exist in the rate and amount of the soil-adsorbed chemical that enters the body; its distribution to tissues; and the rate, amount, and form which is eliminated. Determinations of the bioavailability of metals in soils are needed to assess the risk associated with exposure to contaminated soils.

In this study, a Cd-contaminated soil and a Cd-solution were orally administered to male Lewis rats. By calculating the area under the plasma concentration time curve (AUC), the effect of the soil matrix on the bioavailability of Cd was determined. Furthermore, a material balance was conducted by quantitation of the amounts of Cd absorbed and retained in the body and the amounts excreted into urine and feces.

## Materials and Methods

***Materials.*** Methyl isobutyl keton (MIBK), cadmium nitrate, palladium, and $CdCl_2$ (purity >99%) were purchased from Merck (Amsterdam, The Netherlands). Ammonium pyrollidine dithio-carbamate (APDC) was obtained from Sigma (St. Louis, MO). Analytical grade chemicals were used in all other instances. Water was purified by means of a milli-Q water purification system.

***Animals and maintenance.*** Eight-week-old male Lewis rats at 225 ± 13 g [mean ± standard deviation (SD)] were housed individually in metabolic cages in an air-conditioned room at 21–22°C and 50–55% humidity with a 12-hr dark/12-hr light cycle. The rats were randomly allocated to three different treatment groups. During 4 days of acclimatization, the rats had free access to powdered standard lab chow (diet no. SRM-A; Hope Farms, Woerden, The Netherlands) and drinking water. With

Address correspondence to P.A.E.L. Schilderman, Department of Health Risk Analysis and Toxicology, Maastricht University, P.O. Box 616, 6200 MD, Maastricht, The Netherlands.

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regard to trace elements, the diet of the Cd-saline and the control group contained 0.08 µg Cd/g, whereas the diet of the Cd-soil group contained 0.06 µg Cd/g.

***Cd-saline/Cd-soil solutions.*** The Cd solution was prepared from $CdCl_2$ powder dissolved in isotonic saline (0.9% NaCl) to yield a final concentration of 0.1 mg/liter.

For reasons of standardization and reproducibility, an artificial soil, as developed by the Organisation for Economic Co-operation and Development (OECD) in 1984 and the European Economic Community (EEC) in 1985, was chosen as test substrate. Its absorptive capacity has been assumed to resemble that of a typical loam soil. The artificial soil (particle size <0.5 mm) contained 10% spaghnum, 20% kaolin clay, and 70% fine sand (by dry weight). The soil was spiked in the laboratory with a $CdCl_2$ solution (1 g Cd/liter) and subsequently incubated for 2 weeks on a top-on-top rotator. Final Cd concentration of the soil was 4.4 g/kg. $CaCO_3$ (1%) was added to adjust the pH of the soil to 5.8, following pH limits described by the OECD in 1984 (*19*) and the EEC in 1985 (*20,21*). The organic matter content of the soil was 9.5%. Cu, Pb, Zn, and As concentrations were 1.64, 3.82, 6.36, and 4.75 µg/g, respectively. The passage of soil-containing suspensions through gavage needles was facilitated by pulverizing each soil prior to use. The soil was suspended in an aqueous solution containing 5% gum acacia.

***Test procedure.*** Group 1, the Cd-saline group ($n$ = 6), was orally treated by gavage with 1.5 ml of the $CdCl_2$ solution (150 µg Cd/rat). Group 2, the Cd-soil group ($n$ = 6), was treated by gavage with an aqueous solution containing 1.5-ml 5% gum acacia with 34 mg soil (150 µg Cd/rat). Group 3, controls ($n$ = 6), received 1.5 ml isotonic saline only.

The Cd concentration of the artificial soil (before spiking) was very low; the dose of Cd administered by unspiked soil would be less than 1% and is therefore negligibly low. However, each animal received 1.5 ml 5% gum acacia as a vehicle for administration on the first day, and this solution might affect gastrointestinal absorption of Cd. To evaluate this, the effect of gum acacia on absorption of lab chow Cd, e.g., background levels, was assessed using two animals. No vehicle effect by gum acacia on blood and tissue Cd was apparent. Because there were no differences between these animals and the (saline-) control group, the (saline-) controls were used for both Cd-treatment groups.

The dose level of Cd selected for use in this study was based on single exposure studies to $CdCl_2$ in which doses in the range of 400–900 µg Cd/kg body weight were administered (*22–24*). In this study 150 µg Cd/rat was administered, which corresponds to 650 µg/kg body weight. The amount of soil was based on reported soil exposure levels (*25*). In these studies, soil ingestion was based on the amount of diet consumed daily. On the average, soil ingestion in children was estimated to constitute 0.08% of the diet; for children showing pica behavior, soil constitutes approximately 0.48% of the diet. In this study, the amount of soil administered was equivalent to 0.17% of the diet of animals.

Feed was held from rats for 16 hr prior to oral dosing, whereas drinking water was available *ad libitum*. Immediately after dosing, rats were provided with regular lab chow *ad libitum*. Fresh drinking water was provided at 3-day intervals. In order to calculate the intake of Cd by food, food intake and body weights were recorded daily. All rats were sacrificed under ether anesthesia by exsanguination via the aorta 144 hours after oral dosing. Liver, kidneys, brain, and heart were dissected, washed in ice-cold saline, and stored at -20°C until further analysis. Urine and feces samples were collected in 24-hr fractions during a 144-hr period after administration. Collected urine and feces samples were stored at -20°C.

Serial blood samples were collected by orbital puncture under $CO_2$ anaesthesia. Heparinized blood samples were collected at 0, 10, 20, 30, 60, 120, 240, and 480 min on the first day and at 24-hr intervals on the next 5 days and stored at -20°C.

***Atomic absorption spectrometry (AAS).*** Whole blood samples were taken by means of orbital puncture using heparinized capillary tubes. Immediately after sampling, the blood had to be thoroughly mixed to avoid clotting. Sample preparation was based on Stoeppler and Brandt (*26*). In short, samples were diluted with 1M $HNO_3$ (1:3; v:v) and ultrasonified. After centrifugation, the supernatant was transferred to a sample cup. The ashing temperature was 500°C; the samples were atomized at 1800°C.

One milliliter of slightly acidified urine was mixed with 200 µl of an aqueous 2% APDC-solution and 1 ml MIBK was added. The samples were vigorously mixed for 2 min and centrifuged. The supernatant MIBK-layer was transferred to a sample cup and was directly used for AAS measurements (*26*). An ashing temperature of 550°C and an atomization temperature of 1600°C were used.

Tissue samples (liver, kidney, heart, and brain) were dried at 120°C to a constant weight. Each sample was ground to powder in an agate mortar. After addition of 20 ml of 1:1 mixture of concentrated $HNO_3$ and mQ [ultra pure water purified by a millipore super-Q plus water purification system (Millipore, Ettenieur, The Netherlands)], the samples were boiled for 2 hr on a hot plate. After filtration, the residue was evaporated to a moist residue (2–3 ml) and diluted with 0.1% $HNO_3$. The ashing temperature was 500°C and the samples were atomized at 1,800°C.

Feces samples were treated in the same way as tissue samples.

The Cd content of soil was determined according to NEN 6465 (*27*). Briefly, a soil sample of 0.5 g was boiled under reflux for 2.5 hr in Aqua Regia and then filtrated.

Concentrations of Cd in whole blood, urine, tissues, and feces were measured by graphite furnace AAS with Zeeman (Varian Spectra 400, Mulgrave, Victoria, Australia) background correction (Varian Spectra 10 plus). The Cd concentration in soil was measured by flame AAS with deuterium background correction.

Cd analysis was carried out at 228.8 nm. Paladium nitrate was used in all instances as a modifier and Cd-nitrate solutions in 0.1% $HNO_3$ were used for calibration (external standard line).

Urinary creatinine was measured by a Bio-Rad protein assay. All used glass and plastic labware were precleaned in diluted nitric acid and deionized water to avoid contamination.

***Statistics.*** Results are expressed as mean ± SD. Statistical differences between the treatment groups were determined by the Mann-Whitney $U$-test. A $p$-value less than 0.05 was considered statistically significant.

By calculations of the percentage of the original administered dose, corrections were applied for background levels in the corresponding control groups. The AUC was calculated by the trapezoidal rule using individual data. The relative bioavailability was calculated by the following formula:

$$F_{rel} = (\text{AUC soil}/\text{AUC pure}) \times (\text{dose pure}/\text{dose soil}).$$

## Results

There were no significant differences in mean food intake during the experimental period between the Cd-treated groups and the control group or within the Cd-treated groups (data not shown). The food intake in all groups was reflected by the body weight throughout the experiment. No differences in mean body weight were found between the three different groups. The average daily intake of Cd by food was significantly enhanced in the Cd-saline group (1.28 ± 0.16 µg Cd/day) as compared to the Cd-soil group (0.97 ± 0.16 µg Cd/day; $p$<0.05);

however, the amount of Cd administered by food was negligibly low as compared to the administered dose.

The concentration of Cd in whole blood following oral administration of pure Cd or Cd adsorbed to soil is shown in Figure 1. Overall, the group mean of whole blood Cd concentration values for the Cd-soil group were significantly lower than the blood Cd concentrations of the Cd-saline group ($p<0.05$). Absorption from the gastrointestinal tract was relatively rapid in both Cd-treated groups. Soil induced a small delay in time to reach peak concentrations compared to pure Cd. In the Cd-saline group, a peak concentration of 28.3 ± 4.5 ng/ml was reached after 30 min, whereas in the soil-treated animals a maximum of 13.1 ± 2.4 ng/ml was reached 60 min after oral dosing. During the first 4 hr after oral dosing, there was a sharp decline in blood Cd concentrations (Cd-saline, 8.17 ± 3.13 ng/ml; Cd-soil, 4.18 ± 1.64 ng/ml), which slowed to a more gradual decline between 4 and 24 hr (Cd-saline, 5.4 ± 1.5 ng/ml; Cd-soil, 2.3 ± 0.9 ng/ml). For the next 5 days, the Cd concentrations in blood in both groups remained relatively constant. The background concentration of Cd in blood was 1.40 ± 0.6 ng/ml in the control group. After 144 hr there were no statistically significant differences in blood Cd levels between the three different treatment groups.

The data for the AUC for the 144-hr period after oral dosing are presented in Table 1.

Cd adsorped to soil decreased the bioavailability of Cd to 43% as compared to the Cd-saline solution ($p<0.05$). By determining the relative bioavailability for Cd adsorped to soil, a correction was applied for background levels of Cd in blood as measured in the control group.

The results on excretion of Cd in feces, as shown in Table 2, showed that the major route of excretion of Cd was the feces. Cd in soil was excreted at a comparable rate in feces as compared to the excretion pattern of the Cd-saline treated rats. Within 48 hr following administration, over 70% of the initial dose was recovered in feces of both the Cd-saline and the Cd-soil groups. During the 48–72 hr period, an additional 20% of the administered dose was excreted. During the fifth and the sixth days of the experiment, no significant differences in Cd content in feces were found between the Cd-saline or Cd-soil group and the control group. After 6 days in both Cd-treated groups, over 91% of the initial administered dose was recovered in feces of both Cd-treated groups. Furthermore, 80% of the Cd administered by food was recovered in the feces of the control rats.

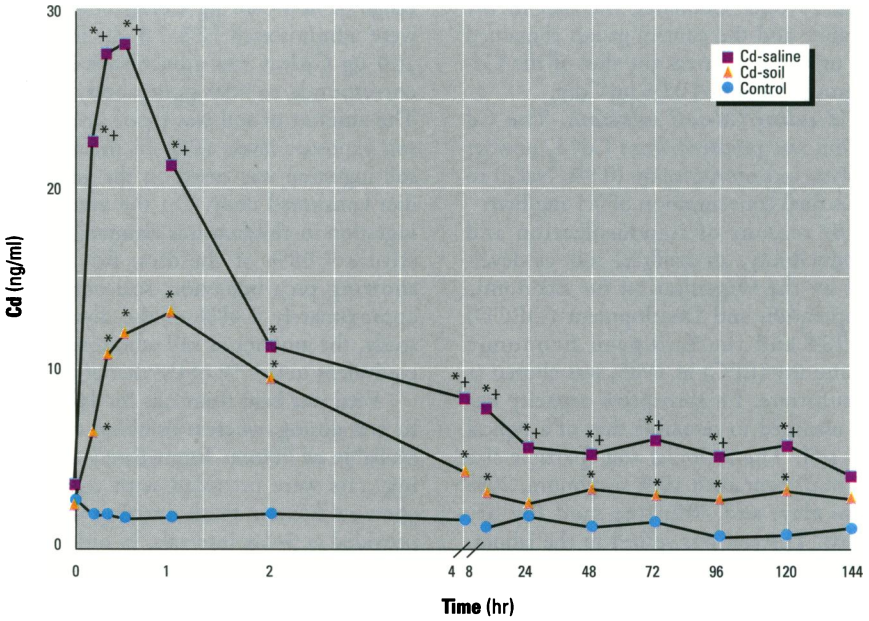


**Figure 1.** Mean Cd concentration in whole blood (ng/ml) during 144-hr period following oral administration of 0 or 150 µg Cd adsorped to soil or dissolved in saline. The statistical significance of differences was determined by the Mann-Whitney *U*-test.
$^{+}p<0.05$ by comparison of Cd-saline with Cd-soil.
$^{*}p<0.05$ by comparing Cd-saline or Cd-soil with the control group.

Large variations were observed in Cd levels in urine between the individual rats of the three different treatment groups (data not shown). In the Cd-saline group, no increase in Cd excretion in urine was observed as compared to the control group. In the Cd-soil group, however, a significant increase in urinary Cd levels was observed during the second day of the experiment by comparison with the control group ($p<0.05$). The amount of Cd recovered in urine in the control groups was, on average, 0.27% of Cd administered by food.

Table 3 presents data on Cd contents in liver, kidney, heart, and brain, expressed as ng Cd/g wet weight (ww). In all the organs examined, there was a significant increase in the Cd content of these tissues by comparison of the Cd-treated groups with the control group ($p<0.05$). Moreover, the Cd concentrations of kidney, heart, and brain tissue of the Cd-saline group were significantly increased as compared to the tissue contents of the Cd-soil group ($p<0.05$).

Cd predominantly accumulated in the liver, with a lower accumulation in the kidney. Cd liver concentrations in the Cd-saline group and the Cd-soil group correspond to 3.70 and 2.59% of the original dose, respectively. The background Cd liver level, as determined in the control group, was less than 10 ng/g ww.

A statistically significant increase was found in Cd content of kidney tissue by comparison of the Cd-saline group with the Cd-soil group ($p<0.05$). In the kidneys of the Cd-saline and the Cd-soil group, Cd concentrations of 262 ± 64 (0.34% of original dose) and 125 ± 36 ng/g ww (0.16% of dose), respectively, were found, whereas in the control group less than 20 ng/g ww was found.

In the heart and brain tissue, relatively low Cd concentrations were found. Cd content of heart tissue of the Cd-saline group (33.1 ± 10.0 ng/g ww) was significantly higher as compared to the Cd content in the Cd-soil group (21.6 ± 4.7 ng/g ww) ($p<0.05$). This corresponds to 0.012 and 0.008% of the administered dose, respectively, in the Cd-saline and Cd-soil groups. Background Cd concentration in the control group was, on average, 7.4 ng/g ww.

In rat brain tissue of the Cd-saline and the Cd-soil group, respectively, 14.2 ± 8.9 and 5.0 ± 1.7 ng/g ww were found, whereas 2.9 ± 2.6 ng Cd/g ww was detected in the control group.

The total recovery of the administered dose (feces, urine, and tissue examined) was 95.5 and 94.5% for the Cd-saline and Cd-soil groups, respectively.

Data on the relative organ weights (data not shown) showed that a single oral dose of pure Cd resulted in a significant increase in relative liver weight as compared to the control group ($p<0.05$). However, Cd adsorped to soil had no effect on relative liver weight. Moreover, a single oral dose of pure Cd or Cd adsorped to soil induced a significant decrease in relative heart weight ($p<0.05$).

**Table 1.** Area under the plasma concentration time curve (AUC) values of rats for the 144-hr period following a single oral dose of Cd

| Treatment | AUC (ng/ml/hr) |
|---|---|
| Cd-saline | 817 ± 169*+ |
| Cd-soil | 421 ± 19* |
| Control | 123 ± 55 |

Statistical significance of differences was determined by the Mann-Whitney *U*-test.
+$p<0.05$ by comparing Cd-saline with Cd-soil.
*$p<0.05$ by comparison of Cd-saline or Cd-soil with the control group.

**Table 2.** Cd excretion in feces of rats during the 6-day period after exposure to a single oral dose of Cd[a]

| Treatment | 0–48 hr | 48–72 hr | 72–96 hr | 96–120 hr | 120–144 hr | Total |
|---|---|---|---|---|---|---|
| Cd-saline | 108.4 ± 11.3* (72.3 ± 7.5) | 23.1 ± 13.02* (15.4 ± 8.7) | 2.58 ± 1.28* (1.7 ± 0.85) | 1.06 ± 0.40 (0.7 ± 0.3) | 1.64 ± 0.4 (1.1 ± 0.3) | 136.8 ± 5.4* (91.2 ± 3.6) |
| Cd-soil | 111.2 ± 15.3* (74.1 ± 10.2) | 21.3 ± 13.7* (14.2 ± 9.1) | 2.58 ± 0.31* (1.7 ± 0.20) | 1.41 ± 0.24 (0.9 ± 0.16) | 1.17 ± 0.11 (0.8 ± 0.07) | 137.6 ± 4.1* (91.7 ± 2.7) |
| Control | 0.82 ± 0.34 | 1.37 ± 0.61 | 1.13 ± 0.36 | 1.38 ±0.64 | 1.63 ± 0.17 | 6.33 ± 0.75 |

Statistical significance of differences was determined by the Mann-Whitney *U*-test.
[a]Expressed as micrograms of Cd per day (% of administered dose).
*$p<0.05$ by comparison of Cd-saline or Cd-soil with the control group.

**Table 3.** Cd content in organs of rats during the 6-day period after exposure to a single oral dose of Cd [a]

| Group | Liver | Kidney | Heart | Brain |
|---|---|---|---|---|
| Cd-saline | 533 ± 126* (3.70 ± 1.06) | 262 ± 64*+ (0.34 ± 0.11) | 33.1 ± 10.0*+ (0.012 ± 0.004) | 14.2 ± 8.9* (0.013 ± 0.010) |
| Cd-soil | 395 ± 101* (2.59 ± 0.73) | 125 ± 36* (0.16 ± 0.04) | 21.6 ± 4.7* (0.008 ± 0.001) | 5.0 ± 1.7* (0.003 ± 0.001) |
| Control | 5.2 ± 1.5 | 19.1 ± 9.1 | 7.5 ± 3.2 | 2.9 ± 2.6 |

Statistical significance of differences was determined by the Mann-Whitney *U*-test.
[a]Expressed as nanogram per gram wet weight (% of administered dose in whole organ).
+$p<0.05$ by comparing Cd-saline with Cd-soil.
*$p<0.05$ by comparison of Cd-saline or Cd-soil with the control group.

## Discussion

The increased industrial uses of Cd during the last few decades has resulted in a concommitant rise in contamination of soil, air, and water (*28*). This increased pollution by Cd has been reflected by an increased body burden of Cd in human populations over the same period (*29*). When evaluating the health hazards posed by exposure to contaminated soils, numerous factors must be considered. One of these factors concerns the bioavailability of soil-bound pollutants. An important factor in determining bioavailability is the speciation of Cd (*8*). Previous studies with laboratory animals showed that insoluble Cd compounds are very rapidly eliminated via the feces with very little bioaccumulation, while soluble compounds caused lung damage and accumulation of Cd in liver and kidneys (*8,30*). The bioavailability of soluble Cd compounds, such as the Cd-salt used in this study, is therefore substantially higher than that of insoluble Cd compounds.

Moreover, the length of time during which the soil has been contaminated may also affect oral bioavailability. Several reports indicate stronger adsorption of chemicals to soil with aging (*11,14*); however, the artificial soil we administered was prepared in the laboratory directly before use, thus the effect of aging might be of minor relevance for the bioavailability of Cd in this study.

This study was performed to assess differences in bioavailability of soil-adsorbed Cd versus pure-form Cd in the male rat following oral administration. Our data indicate that the relative oral bioavailability of soil-adsorped Cd appears to be less than 43%. The relative strong adsorbance of Cd to soil was supported by sustained lower plasma concentrations. Peak plasma concentrations were slightly delayed in the Cd-soil treated rats as compared to the Cd-saline group, which indicates that chemical–soil interactions might be involved.

In both treatment groups, a rapid clearance of Cd from the blood was observed. Four hours after oral dosing, blood Cd levels were only slightly enhanced, by comparison with the control group, whereas blood Cd levels decreased to background levels another 16 hr later, as is in agreement with previous reports (*8,31*).

The lower gastrointestinal absorption of soil-adsorped Cd was reflected in significantly decreased ($p<0.05$) tissue concentrations of Cd in the Cd-soil treated rats as compared to the Cd-saline rats. The tissue distribution pattern was not affected by adsorption of Cd to soil.

Previous studies have shown that the absorption efficiencies in various species after a single oral dose of $CdCl_2$ range from 0.5 to 8% (*7,8,31*). Moreover, young animals appeared to be far more efficient in absorbing and retaining orally administered Cd than adults (*24,32*). The highest organ burden of Cd after a single oral dose of $CdCl_2$ was initially found in the liver, followed by the kidneys (*7,31*). On average 50% of the total body burden will be accumulated in the liver and the kidneys (*7,28*).

In this study, 4.0% of the original dose of Cd accumulated in the liver and kidneys of the Cd-saline group, whereas 2.8% of the initially administered dose was recovered in the same organs of the Cd-soil group. These data fit well within the range found in literature. The high absorption efficiency in this study might be ascribed to the relatively young age of the animals used in this study.

Gastrointestinal absorption amounts to only a few percent of orally ingested Cd, which indicates that most ingested Cd is excreted into the feces (*8,28*).

The results from this study showed that the excretion of Cd in feces in both treatment groups was over 90%; this indicates that only a small amount (<10%) of the administered oral dose is absorbed. This is in agreement with the amount of Cd recovered in the liver and kidney of the Cd-saline group (4%), which is assumed to comprise 50% of the total body burden. Moreover, Cd in soil was excreted in feces at a comparable rate as compared to the salt solution.

Cd excretion into urine in this study was negligibly low. Excretion of Cd into urine is related to body burden, recent exposure, and renal damage (*8*). A high excretion in urine can occur shortly after administration of larger doses of Cd, i.e., doses exceeding 0.1 mg/kg body weight (*8*). The administered dose of Cd in this study was 0.65 mg/kg body weight; therefore, an initially enhanced excretion of Cd into urine might be expected in both Cd-treatment groups. By contrast, a significantly enhanced urinary Cd excretion during the first 2 days of the experiment was only observed in the Cd-soil group. The additional amount of Cd corresponded to only 0.01% of the original dose. No conclusive explanation could be made for these results. A possible explanation for the enhanced urinary Cd excretion could be the repetitive anesthesia on the first day of the experiment, which might affect renal clearance. Saturation of binding sites by other metals present in soil might be another explanation. But, in view of the low concentrations of these metals in the soil, this is very unlikely. Moreover, the

enhanced urinary excretion of soil-adsorped Cd is too low to explain the lower amounts of Cd in the organs examined of the Cd-soil group as compared to the Cd-saline group.

A few studies have been conducted on the bioavailability of soil-adsorped pollutants such as 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD)(*13*), phenanthrene (*10*), polychlorinated biphenyls (*11*), lead (*30*), chromium (*15*), and arsenic (*33*). In all these studies the bioavailability of soil-adsorbed chemicals was significantly decreased as compared to administration of the pure solution. No effect of soil-adsorption was found for trichlorethylene (*34*) and toluene (*35*).

Our study demonstrates that Cd-soil interactions significantly decreased the bioavailability of Cd to enter the body. The bioavailability value in the Cd-soil treated rats was decreased by 57% based on the blood data, by 30% based on the liver data, and by 54% based on the kidney data. By assuming an unchanged bioavailability in exposure assessment models, a considerable overestimation of the internal dose will be made. Furthermore, the degree of reduction of bioavailability of soil contaminants will vary with variations in physicochemical characteristics of the soil matrices involved.

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