An Estimation of the Size Distribution of Amalgam Particles in Dental Treatment Waste

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Abstract. Regulations have been adopted in several countries of the European Union which prescribe that dental treatment waste water must be discharged via an amalgam separator device. Since the effectivity of the device strongly depends on the size of the amalgam waste particles, this size was evaluated in waste water samples from eight dental offices. Per sample, all solid particles were separated from the waste water by pressure filtration, then dried and divided into six fractions by being sieved over five sieves with decreasing mesh width. Of the particles in each fraction, the density was determined by pycnometry, the mass by weighing, and the area and width by image analysis. For this analysis, width was defined as the dimension perpendicular to the length of the particles. By combining the density, area, and width determinations of all fractions, we obtained mass distributions per waste particle width of the samples. The proportional amalgam mass of the distributions was estimated with the measured density of the particle fractions and with a number of assumptions for the density of amalgam particles only and of other waste particles only. Each waste sample has its own characteristics with respect to the mass and density of the particle fractions. The size distribution of waste particles has a bimodal shape and consists of a distribution of small (width, 2 to 90 μm) and large particles (width, 160 to 5500 μm). For small particles with a width up to 60 μm, the influence of the assumptions on the estimation of the proportion amalgam of the waste mass distribution is minor when compared with the sampling error. By averaging the estimations over the samples, one can estimate the weight of amalgam particles with a width < 10 μm and < 50 μm, respectively, between 4 and 15% and between 15 and 30%. The smallest particles comprising 5% of the amalgam mass have an estimated width of up to 5 to 15 μm.

Key words: dental amalgam, mercury, treatment waste, particle size distribution, image analysis.

Introduction

The unusually high mercury concentration of fish caught in the Minimata Bay in Japan in the Fifties and in lakes in Sweden, Canada, and the US in the Sixties led to the discovery of the phenomenon known as mercury methylation (Jensen and Jernelöv, 1969; Goldwater, 1971). The phenomenon is caused by living bacteria which transform inorganic and phenyl mercury compounds in bottom sediment of natural waters into monomethyl mercury (CH3Hg+) and dimethyl mercury (CH3HgCH3). Due to this methylation, mercury enters and subsequently bio-accumulates in the aquatic food chain. This bio-accumulation is generally recognized as a public health hazard, because alkyl mercurials are powerful neurotoxins (Gavis and Ferguson, 1972). To prevent bio-accumulation of mercury in surface waters into which industrial waste water contaminated with mercurials is discharged, laws and regulations have been adopted in most Western countries which resulted in a reduction of the mercury concentration in industrial effluent to acceptable levels (Arenhold-Bindslev, 1992).

For further reduction of mercury contamination of surface waters in countries of the European Union (EU), a directive has been adopted for mercury discharges for sectors which are not industrial plants and to which emission standards cannot be applied in practice (European Economic Community, 1984). According to the directive, member states of the EU are obliged to draw up specific programs for these sectors with the purpose of avoiding or eliminating mercury pollution. The programs must include the most appropriate measures and techniques for the replacement, retention, and recycling of mercury. Dentistry is one of the sectors mentioned in the directive, because of the amalgam waste which is released during the placement and replacement of amalgam fillings and which is discharged into the public sewerage together with waste of other dental treatments. In 25 waste water samples generated daily from dental units, it was found that the average Hg load was 484 mg, which roughly equals 1 g of amalgam (Naleway et al., 1994). Until now, the EEC directive has been implemented for the dentistry sector in national regulations in Germany (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 1989) and The...
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Netherlands (Ministerie van Verkeer en Waterstaat, 1994). Sweden, Norway, and Denmark have adopted regulations that differ from the EEC directive. The German and Dutch regulations prescribe that dental treatment waste water must be discharged by way of an amalgam separator with an effectivity of at least 95%. The equipment of dental operators with an amalgam separator significantly reduces the mercury burden of treatment waste water (Arenholt-Bindslev and Larsen, 1991).

Essential for the effectiveness of retention or separation equipment for amalgam waste is the size of the amalgam waste particles, because the larger the size, the easier particles can be separated. Amalgam particle size has been investigated by a subcommittee of a Dutch government office by x-ray sedigraphy as part of the EEC directive program for dentistry in The Netherlands (Rijkswaterstaat, 1990). For the investigation, amalgam waste was used which had been released during a simulation of the clinical production of amalgam waste. The simulation consisted of the removal of ten MOD amalgam restorations in resin bicuspids; the restorations were then replaced by new amalgams (Letzel et al., 1989). The size of amalgam waste particles also has been investigated in Germany by an engineering agency using laser granulometry, at the request of the Bundeszahnärztekammer (Ingenieurbüro für Grundbau, Bodenmechanik und Umwelttechnik, 1993). For this investigation, the treatment waste used had been produced in a dental clinic in Hamburg, Germany, over a period of 2.5 years. It had been collected in a large drainage tank with a proven capacity to retain 99.9% of the amalgam waste. The results of both investigations are depicted in Fig. 1. The cumulative amalgam particle size distributions have more or less the same shape and range from a few tenths of a micron to about 5 mm. Findings from other analyses of amalgam particles in dental waste water illustrate the need for such waste to be further characterized so that removal technology can be developed and evaluated (Arenholt-Bindslev and Larsen, 1991). Essential for the effectiveness of retention or separation equipment for amalgam waste is the density of amalgam restorations in resin bicuspids; the restorations were then replaced by new amalgams (Letzel et al., 1989), because it is often suggested that amalgam waste consists mainly of very fine particles.

Also essential for the effectiveness of retention equipment for amalgam waste is the density of amalgam particles, because the heavier they are, the faster they settle and thus, the easier they are retained. This density is unknown because it has not been relevant to dentistry until now. It depends on the chemical composition of the amalgam alloy and the Hg/alloy ratio at mixing. The density of clinically placed amalgam restorations is lower because of porosity (Marshall et al., 1987) and a lesser Hg content in the amalgam than at mixing (Marshall et al., 1989). The density of aged amalgam is still lower, due to microstructural changes and corrosion of the amalgam (Boyer and Edie, 1990; Marshall et al., 1992).

Due to the limited information on the size distribution of amalgam particles in waste water, we investigated it in waste water samples from several dental offices.

Figure 1. Cumulative mass distribution of amalgam particles determined by x-ray sedigraphy (---) (Rijkswaterstaat, 1990) and by laser granulometry (-----) (Ingenieurbüro für Grundbau, Bodenmechanik und Umwelttechnik, 1993). Curves are transformations of the original data as published by the authors.

Materials and methods

Waste sample collection

For the investigation, eight general practitioners in the Nijmegen area were asked to collect treatment waste during a period of about one week in a mobile aspirator placed next to the dental unit and to record the number of amalgam restorations removed and placed during that period. The aspirator (Orosuc, Durr-Dental, Bietigheim, Germany, or Aspi-jet 6, Cattany, Parma, Italy) consisted of two suction hoses, an air pump, an air-water separation device, and a waste container, and had no connections to the drain of the dental unit. The patient, the operator, and the dental nurse were instructed to use the suction hoses of the aspirator for all treatments during the waste collection period. At the end of each treatment day, the suction hoses were flushed with a natrium-hypochlorite-based disinfection fluid (Hydrosept, Denteck, Zoetermeer, The Netherlands). After the waste was collected, treatment waste retained in the hoses and other parts of the aspirator was carefully removed by a dental service mechanic and added to the collected waste. In this way, eight waste water samples were obtained.

Sample preparation

Initially, large waste floating on the sample, such as cotton wool pellets and wooden wedges, was collected, rinsed with ultrapure water, and then removed. Next, we separated the solid particles from the waste water by flowing the sample into a pressure filtration unit (Type 142/17/3, Schleicher and Schuell, Dassel, Germany) (air pressure, 3.5 bar). The unit consisted of a 1.5-L Teflon infusion vessel and a cellulose-nitrate filter disk (Ø 142 mm; mesh width, 0.45 μm). The filter disk was renewed when the pores of the filter became clogged with fine particles. About four disks were necessary to treat each sample. The concentration of dissolved mercury (including the mercury in amalgam particles < 0.45 μm) in the effluent after filtration of one sample (No. 3, effluent 2.5 L) was determined with Atomic Absorption Spectrometry (Nederlands Normaal instituut,
To improve the efficiency of the filtration process, we first decanted the bulk of the waste water of the last four samples from the sedimenter solid waste. The potential loss of amalgam particles by this procedure was checked by evaporation of the decanted water at 40 ± 2°C and by analysis of the residue on traces of amalgam with SEM/EDX (SEM 505/EDAX, Philips, Eindhoven, The Netherlands).

We removed the waste residue on the filter disks by rinsing the disks with ultra-pure water, which was continued until the disks were totally clean (visual examination). Next, the waste residue was dried at 40 ± 2°C. After being dried, the residue formed a kind of sheet due to a clogging effect of organic substances including cotton wool fibers. Therefore, the sheet was carefully disintegrated with about 100 mL of methanol and a glass stirring rod. After the methanol was evaporated at 40 ± 2°C, the particles and the fibers were washed out over a 212-μm sieve, so that the particles were divided into two fractions. After re-vaporization of the methanol, two particle fractions were obtained. The fraction > 212 μm and the fraction < 212 μm had a granular- and powder-like structure, respectively. The large-particle fraction was further divided into five fractions by being dry-sieved over four sieves with decreasing mesh width (2000, 1000, 500, and 250 μm) (Octagon 300, ELE-intertest, Etten-Leur, The Netherlands). The mass of each of the six sieve fractions was determined by weighing. Next, the total mass and the mass percentage per fraction of the samples were calculated.

Particle size analysis

The size and the size distribution of the waste particles within each of the six sieve fractions were determined per sample on images of the particles obtained with a scanning electron microscope (SEM 505, Philips, Eindhoven, The Netherlands). At random, a small quantity of a sieve fraction was placed on the stub, which was first covered with a slightly electrostatic carbon tab, so that oblong particles would lie flat on the stub surface. Examples of obtained SEM images of waste particles are shown in Fig. 2. The analog SEM images were digitized with a TV interface. Next, the area of the images was determined by means of an image-analyzing software package (Quantimet 500, Leica Cambridge, Cambridge, United Kingdom). We determined the area by counting pixels of the images. For the conversion of pixel count to area, a calibration was made with an image of an object with known dimensions. The lengths of images of the particles were estimated by measurement of the Feret, or caliper diameter, of the images at eight different scan angles (Russ, 1990; Quantimet 500, 1992). The Feret diameter of an image at scan angle is the orthogonal distance between a pair of tangent lines to the image at angle θ (Fig. 3). The maximum of the eight measured Feret diameters was taken as the estimator for the length of the images. Next, the width of each image was estimated as the Feret diameter perpendicular to the maximum (length) Feret diameter. To estimate the volume of the particles, we assumed that the height of the particles equals the width, because all particles lay flat on the stub surface. Thus, the volume of the particles was estimated to be: V\text{particle} = \text{Area} \times \text{Width}. From the large sieve fractions (500 to 1000 μm, 1000 to 2000 μm, > 2000 μm), the volume of all particles divided over several images was estimated. From the small sieve fractions (< 212 μm, 215 to 250 μm, 250 to 500 μm), the volume of a minimum of 100 particles also divided over several images was estimated, thus ensuring a representative sample of particles. With the information on the volume of the particles within each sieve fraction and the mass percentages per sieve fraction, the proportional cumulative mass per waste particle width was calculated for each sample. The resulting mass curve of sample 5, as a representative example, is shown graphically in Fig. 4.

With the remaining parts of the fractions, the density of the waste particles per sieve fraction and per sample was determined by pycnometry.

Amalgam mass estimation

To investigate the amount of amalgam mass of the waste particles, we re-cast the cumulative mass curves of the samples into mass percentages per waste particle width. For this, the total particle width range was divided into 25 sections, and the waste mass percentage was calculated for each section. The re-casting of the mass curve of sample 5 is
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Figure 3. Feret diameter of an image at scan angle $\theta$.

shown as a histogram in Fig. 5. Since the section widths are not equal with respect to particle size, the ordinate does not show the frequency itself, but rather the relative frequency (= frequency density). The density values of the six fractions of sample 5 are also depicted in Fig. 5. Columns of particle width sections within the same sieve fraction have the same density value.

The amalgam mass percentage of the waste mass percentage per waste particle width section ($\text{AMass\%}$) can be calculated according to:

$$\text{AMass\%} = \frac{(1 - \rho_a/\rho)/(1 - \rho_t/\rho)}{100}$$  \hspace{1cm} (1)

where $\rho$ = density of all waste particles together, $\rho_a$ = density of amalgam particles only, and $\rho_t$ = density of other waste particles only. The formula is derived from the equations:

$$V_p = V_a \rho_a + (V - V_a) \rho_t$$

and

$$\text{AMass\%} = \left(\frac{V_a \rho_a}{V_p}\right) - 100,$$

where $V$ and $V_a$ are the volume of all waste particles together and of amalgam waste particles only, respectively. Since $\rho_a$ and $\rho_t$ cannot be determined because the amalgam particles are mixed with other waste particles, and since $\rho$ is measured over only a few width sections, $\text{AMass\%}$ was estimated based on formula (1), with the following assumptions:

(1) Waste particles other than amalgam particles ($\rho_a$) are of mainly biological origin. When such particles settle, their density is somewhat larger than 1. Therefore, $\rho_t$ was set to 1.1 g/cm$^3$.

(2) The density of amalgam can be estimated when the chemical composition of the amalgam alloy system and the alloy-Hg ratio at mixing is known. Such estimations for three alloy systems are listed in Table 1, indicating a density of 11.3 to 11.6 g/cm$^3$. Of four amalgam restorations retrieved from posterior teeth and which were placed about 15 years before the teeth were removed for periodontal reasons, the density was determined by picnometry. The mean was 9.3 g/cm$^3$ (SD = 2.0). Based on these estimations and determinations, it was assumed that the density of amalgam particles ($\rho_a$) ranges between 9 and 11 g/cm$^3$.

(3) Small amalgam particles arise when aged restorations are removed by being drilled and ground with rotating instruments and are assumed to have a width $< 212 \mu$m. On the other hand, large particles (assumed width $> 212 \mu$m) are released when new restorations are placed during

Table 1. Estimated density of amalgam made of three alloy systems

<table>
<thead>
<tr>
<th>System</th>
<th>Trade Name, Manufacturer (source of composition)</th>
<th>Ag</th>
<th>Sn</th>
<th>Cu</th>
<th>Hg</th>
<th>Density$^b$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>New True Dentalloy, S.S. White Co., Philadelphia, USA$^c$</td>
<td>35.0</td>
<td>13.0</td>
<td>2.0</td>
<td>50.0</td>
<td>11.6</td>
</tr>
<tr>
<td>High-Cu</td>
<td>Cavex non-gamma-2, Cavex, Haarlem, The Netherlands$^d$</td>
<td>34.5</td>
<td>9.5</td>
<td>6.0</td>
<td>50.0</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td>Luxelloy, Degussa, Frankfort, Germany$^e$</td>
<td>34.0</td>
<td>9.0</td>
<td>6.0</td>
<td>50.0</td>
<td>11.6</td>
</tr>
<tr>
<td>Low-Ag</td>
<td>Avalloy, Cavex, Haarlem, The Netherlands$^d$</td>
<td>22.5</td>
<td>15.5</td>
<td>12.0</td>
<td>50.0</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>Duralloy, Degussa, Frankfort, Germany$^e$</td>
<td>25.0</td>
<td>15.5</td>
<td>10.0</td>
<td>50.0</td>
<td>11.4</td>
</tr>
</tbody>
</table>

$^a$ Alloy-Hg ratio, 1:1.
$^b$ Density of Ag, Sn, Cu, and Hg, respectively, 10.5, 7.3, 9.0, and 13.5 at 293°K (Weast, 1989).
$^d$ Cavex Holland BV, 1993.
$^e$ Bengel, 1990.
condensation, burnish, and carving of freshly mixed amalgam. Thus, $p_a$ of amalgam particles with a width < 212 µm and > 212 µm was assumed to be 9 and 11 g/cm³, respectively. However, small amalgam particles also arise when new amalgam restorations are polished, and large particles are also produced during the removal of aged restorations, when amalgam remnants of heavily corroded restorations break out of the cavity. Therefore, four assumptions regarding the density of small and large amalgam particles were considered: $p_a$ particles < 212 µm - $p_a$ particles > 212 µm = 11-11, 9-9, 9-11, and 11-9 g/cm³.

(4) The density of all waste particles (p) in the fraction < 212 µm is variable, although only one density parameter for this fraction was available. The variability was assumed to have three forms:

(a) Absent variation (AV): All waste particle width sections have the same $p$. For sample 3, this form is shown graphically in Fig. 5A with *'s.
(b) Positive variation (PV): The larger the particles within the fraction, the higher is $p$. The magnitude of the variation is taken to be the same as that of the measured density of the other fractions of the sample (Fig. 5B).
(c) Negative variation (NV): The larger the particles within the fraction, the lower is $p$. The magnitude of NV is taken to be the same as that of PV (see Fig. 5C).

When assumptions (3) and (4) are combined, the AMass% can be estimated on 12 different modes. In Table 2, the modes are summarized and coded. For each sample, the 12 AMass% estimations were calculated. Next, the mean of the AMass%, including the standard error of the samples, was calculated for each estimation mode. The means of the AMass% were also listed in a cumulative form, resulting in a mean cumulative amalgam mass curve per waste particle width section for each estimation mode. The influence of the estimation mode (and thus the assumptions) was investigated by comparison of the shapes of the 12 curves.

Results

The sampling time and the number of removed and placed amalgam restorations per hour are listed per dental office in Table 3.

The concentration of dissolved Hg in the 2.5-L effluent after filtration of sample 3 was 2.6 mg/L, which corresponds with a total amount of dissolved Hg in this sample of 6.5 mg. No traces of amalgam have been found in the residue of evaporated water, which was decanted from four samples after sedimentation of solid particles to improve the efficiency of the filtration process.

The mass of the produced solid waste particles and the mass percentage per sieve fraction are given for each waste sample in Tables 3 and 4, respectively. The density of the waste particles per sieve fraction is also listed in Table 4. It was not possible to determine the density of the fraction > 2000 µm of samples 2 and 7 and of all fractions of sample 3, because they were used to test the feasibility of particle size determination of dental treatment waste by image analysis. Sample 7 contains the two fractions with the lowest density (0.63 and 0.95 g/cm³) and sample 2 the two fractions with the highest density (11.98 and 12.96 g/cm³).
The mass per waste particle width of sample 5, depicted as a proportional cumulative curve in Fig. 4 and as a histogram in Fig. 5, show that the sample consists of two types of particles—small (< 30 μm) and large (> 200 μm)—and that the sample contains practically no particles in the range of 30 to 240 μm. Except for sample 7, the mass curves of the other samples have the same bimodal shape. The minimum and maximum widths of small and large particles are listed per sample in Table 5, which also lists the mass percentage of all small particles together per sample, so that, with the five parameters, the bimodal shapes of seven of the eight mass curves are characterized.

To estimate the amalgam mass percentage of the waste mass percentage per waste particle width section (AMass%), we extrapolated the missing density parameters of some fractions of Samples 2 and 7 (Table 4) from those of the other fractions. Sample 3 was excluded for the AMass% estimations, because none of the density parameters of the fractions was available. For Sample 5, the AMass% estimated according to mode AVI1-11, PV11-9, and NV9-11 are shown graphically in Figs. 5A, 5B, and 5C, respectively.

The comparison of the shapes of the 12 mean cumulative amalgam mass curves per waste particle width section for investigation of the influence of the AMass% estimation mode revealed that the shape difference was the largest when the AMass% were estimated with modes PV11-9 and NV9-11. This shape difference is shown in Fig. 6. The influence of the sample on the shapes of the two curves is illustrated with standard errors of the mean.

Table 3. The sampling time, the hourly removal and placement of amalgam fillings, and the mass of the solid waste particles produced per dental office

<table>
<thead>
<tr>
<th>Dental Office</th>
<th>Sampling Time (days)</th>
<th>Amalgam Fillings per Hour Removed</th>
<th>Placed</th>
<th>Total</th>
<th>Per Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>0.59</td>
<td>0.76</td>
<td>22.45</td>
<td>0.66</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>0.45</td>
<td>0.66</td>
<td>8.71</td>
<td>0.30</td>
</tr>
<tr>
<td>3</td>
<td>29</td>
<td>0.62</td>
<td>0.32</td>
<td>25.74</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>0.27</td>
<td>0.32</td>
<td>11.55</td>
<td>0.32</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>0.68</td>
<td>1.16</td>
<td>22.31</td>
<td>0.59</td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td>0.42</td>
<td>0.28</td>
<td>10.96</td>
<td>0.30</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>0.26</td>
<td>0.21</td>
<td>5.62</td>
<td>0.30</td>
</tr>
<tr>
<td>8</td>
<td>36</td>
<td>1.14</td>
<td>1.44</td>
<td>28.05</td>
<td>0.78</td>
</tr>
<tr>
<td>Mean</td>
<td>30</td>
<td>0.55</td>
<td>0.69</td>
<td>0.54</td>
<td>0.23</td>
</tr>
<tr>
<td>SD</td>
<td>7</td>
<td>0.28</td>
<td>0.44</td>
<td></td>
<td>0.23</td>
</tr>
</tbody>
</table>

The numbers of amalgam restorations, however, are only estimates, because the treatment waste of only a small and incidental sample of dental offices was collected during a relatively short period. For a more accurate estimate of the treatment waste production, a random and larger sample of dental offices must be used, and the waste must be collected for a longer time than was done in this study.

To measure the size distribution of solid particles in treatment waste water directly and to estimate the percentage amalgam particles of the solid particles, we developed a method for which the solid particles were first separated from the waste water by pressure filtration. Essential to a correct filtration process is that no amalgam particles are lost. We had checked this potential loss by determining the mass of the dissolved mercury in the effluent of one sample (No. 3). This mass was 6.5 mg, which is roughly equivalent to 13 mg of amalgam. Given the total mass of solid waste of sample 3, 25.74 g (Table 3), the mass of dissolved amalgam is 0.05%. This low percentage was the reason we did not check the effluent of the other samples on dissolved amalgam. By decanting the bulk of the waste water after sedimentation of solid particles, as has been done for four samples to improve the efficiency of the filtration process, it is possible that floating waste on and suspended waste in the sample were removed. This efficiency measure, however, did not result in a detectable loss of amalgam particles. Therefore, it can be concluded that only some amalgam is lost during pressure filtration of the waste sample. The amount, however, is so small that it has a negligible influence on further analyses.

To prepare the waste particles for division into sieve fractions, we dried the particles twice at 40 ± 2°C. At this temperature, which is slightly higher than oral temperature, mercury loss by evaporation is negligible. During the sieving, dry waste particles can be rounded off and oblong particles can be broken into smaller particles. The relevance of these potential sample preparation effects on the mass and the density determination of the fractions and thus on further analyses is unknown. However, the sample preparation was carried out very carefully; no forces except...
Gravitation were applied, so it is expected that preparation effects were minimal.

The results of the weighing of the sieve fractions (Table 4) show a large variation among the samples with respect to the mass percentage of the fractions. This is caused by differences among the dental offices, such as the kinds of dental care performed and the treatment habits of the operator.

The density values as listed in Table 4 again show a large among-sample variation, which also is caused by differences among the dental offices. Two fractions of sample 7 have a density smaller than one. Probably, these fractions consisted only of organic material. Two fractions of sample 2 have a density which is higher than the maximum estimated density of amalgam (Table 1). Since the density of a 75 wt% dental gold alloy is about 16 g/cm³, the fractions probably contained some gold alloy chips, created during the removal of a cast gold restoration by means of rotating instruments.

Gold alloy particles in treatment waste throw off the measurement of the amount of amalgam mass, when this mass is estimated with the density of the waste. The wide variety in the densities and the mass percentages of the sieve fractions stresses the need for analysis of the chemical composition of treatment waste.

The results of the waste particle size analysis, as depicted in Figs. 4 and 5 for sample 5 and summarized for all samples in Table 5, show a characteristic shape of the particle size distribution of seven of the eight waste samples. In fact, the distribution is a mixture of two distributions, the first consisting of small particles with a range between 2 and 90 μm, and the second containing the larger particles between 160 μm and 5.5 mm. Although the size distributions of this study contain all solid waste particles, most of them resemble the distributions obtained in other investigations which consist of amalgam waste particles only (Fig. 1) (Rijkswaterstaat, 1990; Ingenieurbüro für Grundbau, Bodenmechanik und Umweltechnik, 1993). An explanation of the characteristic shape could be that small particles arise mainly when hard tooth structure and tooth restorations are drilled, ground, and polished. Large particles, on the other hand, are released by other treatments. The deviating shape of the particle size distribution of sample 7 might be caused by the specific treatment habits of the operator.

The method used in this study to determine the size distribution of solid waste particles by the analysis of SEM images of the particles is relatively new. The use of Feret diameters of images as estimators for the length and width of the particles may lead to an overestimation of the volume of the particles. However, the overestimation has no influence on the size distribution of the particles. There are methods by which amalgam particles are first separated from other particles, such as x-ray sedigraphy (Rijkswaterstaat, 1990) and laser granulometry (Ingenieurbüro für Grundbau, Bodenmechanik und Umweltechnik, 1993). Since all methods are vulnerable to systematic errors, the method itself can have an influence on the results. Therefore, the suitability of the methods, including others such as the Coulter Technique (Batchu et al., 1995), needs to be evaluated. This can best be done if they are used simultaneously for the same dental treatment waste water samples.

The results of the estimations of the proportion of amalgam particles in the solid waste particles contain two sources of uncertainty: the density assumptions of certain types of waste particles, and the number of samples. The first source is comprised of the density assumptions of waste particles other than amalgam (p₁), of amalgam particles only (p₂), and of all waste particles together of the sieve fraction < 212 μm (p). For p, the value 1.1 g/cm³ was chosen. In equation (1), it can be seen that this choice does not influence the estimation of the size distribution of amalgam particles. For p₂, two values were adopted. The first value (11 g/cm³) was thought to be a reasonable assumption for the density of amalgam particles released during the placement of new amalgam restorations. The second value (9 g/cm³) was a density estimation of heavily corroded amalgam waste particles released during the replacement of failed and/or old amalgams. When amalgam particles of all sizes have the same density, the value of p₂ has no influence on the estimation of the amalgam particle size distribution, because the denominator of equation (1) is a constant. When p₂ of small particles is different from that of large particles (which is a realistic clinical assumption), p₂ has some influence on the cumulative amalgam mass curve and thus on the size distribution of amalgam particles. The variation of p within the sieve fraction < 212 μm has a similar influence. The extension of both influences together is illustrated in Fig. 6. For the smallest particles with a width up to 60 μm, this

<table>
<thead>
<tr>
<th>Sample</th>
<th>Waste</th>
<th>Sieve Fraction (mesh width in μm)</th>
<th>250-500</th>
<th>500-1000</th>
<th>1000-2000</th>
<th>2000 &lt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt; 212</td>
<td>212-250</td>
<td>250-500</td>
<td>500-1000</td>
<td>1000-2000</td>
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<td>(---)</td>
<td>10.1</td>
<td>(9.39)</td>
</tr>
<tr>
<td>3</td>
<td>49</td>
<td>(---)</td>
<td>2.7</td>
<td>(---)</td>
<td>12.7</td>
<td>(---)</td>
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<tr>
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<td>19.5</td>
<td>(3.18)</td>
<td>2.9</td>
<td>(1.46)</td>
<td>14.6</td>
<td>(4.15)</td>
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<tr>
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<td>9.9</td>
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<td>(3.31)</td>
<td>2.5</td>
<td>(1.06)</td>
<td>7.3</td>
<td>(2.73)</td>
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<tr>
<td>7</td>
<td>58</td>
<td>(2.92)</td>
<td>3.5</td>
<td>(0.63)</td>
<td>17.2</td>
<td>(2.06)</td>
</tr>
<tr>
<td>8</td>
<td>18.8</td>
<td>(5.15)</td>
<td>1.7</td>
<td>(1.80)</td>
<td>10.4</td>
<td>(5.80)</td>
</tr>
</tbody>
</table>

Table 4. The mass percentage and the density in g/cm³ (between brackets) of waste particles per sieve fraction and per sample.

---

* Insufficient mass for density determination.
Table 5. The width range of small and large particles and the mass of all small particles together per sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>Small Particles</th>
<th>Large Particles</th>
<th>Mass of Small Particles (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width Range (µm)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
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</tr>
</tbody>
</table>

* Not detectable.

extension is minor. Therefore, it can be concluded that for the smallest particles the density assumptions of $\rho_p \rho_v$ and $\rho$ of the sieve fraction < 212 µm, which together form the first source of uncertainty, have no relevant influence on the estimation of the amalgam particle size distribution. The weight of amalgam particles with a width < 10 µm and < 50 µm can be estimated between 4 and 15% and between 15 and 30%, respectively. The density of amalgam and other waste particles per particle width needs to be determined, so that the assumptions can be replaced by realistic values.

Regarding the second source of uncertainty, the number of samples, this number was rather small (7). This resulted in large standard errors of the mean cumulative amalgam mass curve (Fig. 6). In the Fig., it can be seen that, compared with the influence of the density assumptions, the influence of the number of samples on the shape of the amalgam mass curve of the particles with a width up to about 60 µm is much greater. To reduce the size of the standard errors to a third and to a fourth, $7 \times 3^2 = 63$ and $7 \times 4^2 = 112$ samples are needed, respectively. Although such large numbers offer the opportunity for a random sample of operators to be drawn and certainly will lead to more accurate estimations, the collection and analysis of large numbers of waste samples are time-consuming and expensive. Therefore, the minimum acceptable number of waste samples must be ascertained. Nevertheless, it can be concluded that the amalgam waste produced in this study does not consist mainly of very fine particles. This is in contrast to what is often suggested in informal discussions on the necessary requirements of amalgam separators.

German and Dutch regulations prescribe that dental treatment waste must be discharged by way of an amalgam separator with a separation effectiveness of at least 95%. Since the smallest amalgam particles are the most difficult to separate, the results of this study were used to estimate the maximum width of the smallest amalgam particles, which together form 5% of the amalgam mass. The result of this estimation is depicted in Fig. 6 with arrows and indicates a width between 5 and 15 µm. Fig. 6 can serve as a guideline for the design and testing of amalgam separation technology.

Figure 6. Cumulative amalgam mass of seven waste samples per waste particle width section according to estimation mode PV11-9 (----) and NV9-11 (........). For codes, see Table 2. Vertical lines represent standard errors of the mean. Range between arrows indicates the maximum width of the smallest amalgam particles which together form 5% of the amalgam mass.

Acknowledgments

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References