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^{210}Po poisoning as possible cause of death: forensic investigations and toxicological analysis of the remains of Yasser Arafat



Pascal Froidevaux^a, François Bochud^{a,*}, Sébastien Baechler^a, Vincent Castella^b, Marc Augsburger^b, Claude Bailat^a, Katarzyna Michaud^b, Marietta Straub^a, Marco Pecchia^c, Theo M. Jenk^c, Tanya Uldin^b, Patrice Mangin^b

^a Institute of Radiation Physics, Lausanne University Hospital, Lausanne, Switzerland

^b University Centre of Legal Medicine, Lausanne and Geneva, Switzerland

^c Paul Scherrer Institute, Villigen, Switzerland

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ABSTRACT

The late president of the Palestinian Authority, Yasser Arafat, died in November 2004 in Percy Hospital, one month after having experienced a sudden onset of symptoms that included severe nausea, vomiting, diarrhoea and abdominal pain and which were followed by multiple organ failure. In spite of numerous investigations performed in France, the pathophysiological mechanisms at the origin of the symptoms could not be identified. In 2011, we found abnormal levels of polonium-210 (^{210}Po) in some of Arafat's belongings that were worn during his final hospital stay and which were stained with biological fluids. This finding led to the exhumation of Arafat's remains in 2012. Significantly higher (up to 20 times) activities of ^{210}Po and lead-210 (^{210}Pb) were found in the ribs, iliac crest and sternum specimens compared to reference samples from the literature (p -value <1%). In all specimens from the tomb, ^{210}Po activity was supported by a similar activity of ^{210}Pb . Biokinetic calculations demonstrated that a ^{210}Pb impurity, as identified in a commercial source of 3 MBq of ^{210}Po , may be responsible for the activities measured in Arafat's belongings and remains 8 years after his death. The absence of myelosuppression and hair loss in Mr Arafat's case compared to Mr Litvinenko's, the only known case of malicious poisoning with ^{210}Po , could be explained by differences in the time delivery-scheme of intake. In conclusion, statistical Bayesian analysis combining all the evidence gathered in our forensic expert report moderately supports the proposition that Mr Arafat was poisoned by ^{210}Po .

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1. Introduction

The following presentation of the background events leading to President Yasser Arafat's death is based on the reading and analysis of the medical records provided to us by Mrs Suha Arafat, widow of Yasser Arafat and next of kin [1].

President Arafat was born on August 4th, 1929. For over three years prior to his death, he remained secluded in the quarters of the Palestinian Authority in Ramallah. He was said to be in general good health, and did not drink alcohol or smoke tobacco. On the evening of October 12th, 2004, approximately four hours after a meal, Yasser Arafat experienced severe nausea, vomiting, and abdominal pain followed by watery diarrhoea. On October 25th,

2004, a bone marrow aspiration analyzed in Tunis showed a well populated bone marrow with mild myelodysplastic changes, the presence of megakaryocytes and an increased number of macrophages with hemophagocytic changes. An infectious work-up, including blood, fecal and urine cultures and an immunological evaluation were considered as normal. On October 29th, 2004, President Yasser Arafat was transferred to the French Military Hospital of Percy in Clamart, France. At the time he arrived in France, the diagnostic list included inflammatory enterocolitis, severe disseminated intravascular coagulation (DIC) with significant thrombocytopenia and bone marrow hemophagocytosis. Shortly after admission, the patient developed liver problems with cholestatic jaundice. The patient did not develop fever and the infectious work-ups, including AIDS tests, remained negative. All the microbiological investigations, as well as a urine test for the presence of gamma ray emitting radionuclides, were negative. Infectious, autoimmune or vascular processes, as well as a pathological tumour were decided to be very unlikely. Toxicological

* Corresponding author at: Institute of Radiation Physics, Lausanne University Hospital, Lausanne, Switzerland. Tel.: +41 213148142.

E-mail address: francois.bochud@chuv.ch (F. Bochud).

tests carried out by the Institute of Criminal Investigation of the French Gendarmerie (Institut de Recherche Criminelle de la Gendarmerie, IRCG) on blood, urine, cerebrospinal fluid and stool taken on the 1st and 4th of November, 2004, revealed only the presence of the medication prescribed by the hospital. Further analyses were performed in urine and faeces on November 8th by the Radiological Protection Service of the French Armed Forces to search for radioactive substances based only on gamma emission, without positive results. The patient developed acute renal failure on November 6th, 2004. On November 11th, 2004 at 3:30 am, President Arafat died as a result of cerebral herniation secondary to cerebral haemorrhage. Despite the number of medical experts involved and the numerous investigations performed, the pathophysiological mechanisms at the origin of the group of symptoms experienced by Yasser Arafat could not be identified and no autopsy was performed. According to two letters dated from April 2nd, 2012 and June 11th, 2012 from the Directorate of Radiation Protection of the Army (Service de Protection Radiologique des Armées, France) to our attention and one letter dated April 2nd, 2012 from the Directorate of the IRCG to the attention of Mrs Suha Arafat, the biological samples for toxicological and radio-toxicological analyses that were taken during his hospitalisation were destroyed in 2008.

Following upon the assassination of Alexander Litvinenko in London in November 2006 by ingestion of polonium-210 (^{210}Po), a suggestion was made that Arafat could have been poisoned in a similar manner. ^{210}Po is a short lived ($T_{1/2} = 138$ d) alpha emitter [2], which typically creates damage on a submillimetre scale, notably to the gastro-intestinal tract if ingested and then to inner organs and bone marrow via blood distribution.

On February 2012, Mrs Suha Arafat presented a bag containing Yasser Arafat's belongings from his final hospital stay, to the University Centre of Legal Medicine (CURML). She gave us her consent that we carry out all the necessary toxicological investigations that could potentially lead to new information about her late husband's death. She also gave us a signed letter giving explicit permission to publication in the scientific literature once our Final Expert Forensic Report had been handed to her and subsequently made public. The Institute of Radiation Physics (IRA) works in close collaboration with CURML in the use of radiometric measurements in forensic science [3,4]. The search for ^{210}Po in the belongings was proposed within the context of current knowledge regarding Litvinenko's poisoning. From a medico-legal perspective, the hypothesis of poisoning with ^{210}Po was justified given the absence of a characterised cause of illness and the absence of toxicological evidence, including gamma radiations. Additionally, to medico-legal experts, the sudden onset of violent gastrointestinal symptoms following a meal in a patient otherwise in general good health may indicate poisoning.

After studying the medical files in detail, we performed a workup on genetic identification as well as toxicology and radioactivity measurements on Yasser Arafat's belongings that we received. Our preliminary results of ^{210}Po identification in the biological stains at unexpected levels of activity [5] led to the exhumation of the body, which took place in Ramallah on November 27th, 2012. At this time, several specimens of bones, scalp, shroud, tooth and soil were taken from the corpse and the grave for toxicological analysis, focusing mainly on ^{210}Po measurement. We report here the results of our full investigation concerning Yasser Arafat's death and the possible involvement of ^{210}Po as a cause of his death.

2. Materials and methods

2.1. Exhumation procedure

We were requested to act as an expert team for the Palestinian Authority and Mrs Suha Arafat (hereinafter called the Swiss team).

The Swiss team was composed of a medico legal expert, a radiation physicist, a radiochemist, a forensic anthropologist and a mortuary technician. A French team, acting on behalf of the French Justice Department after Suha Arafat launched a court case in Paris, and a Russian team, acting as an expert team on behalf of the Palestinian Authority, were also present during the exhumation. The evening before the opening of the tomb, we perforated a 12 mm diameter hole through the grave slab to measure the ^{222}Rn gas concentration (AlphaGuard, Genitron Instruments, Germany). It was essential to determine the ^{222}Rn air volume activity because ^{222}Rn is the precursor of diagenetic ^{210}Pb and ^{210}Po which will deposit on the grave surfaces and possibly contaminate the remains. In fact, during diagenesis, a bone may accumulate contaminants from the burial environment, yielding a radionuclide activity that is in excess of the bone's biogenically derived activity [4]. The exhumation took place the following morning, on November 27th, 2012. During the exhumation, the almost completely skeletonised corpse was not moved, but specimens from the remains (mainly fragments of bones and scalp) and surrounding materials (soil and shroud) were collected by a Palestinian medico legal expert in the presence of representatives from all teams. The state of Arafat's remains meant that it was not possible to identify organs specifically targeted by polonium such as soft tissues. This was a major drawback since polonium is not a bone-seeking radionuclide. All three teams received 20 similar specimens, whose description can be found in supplementary information (SI) provided on the website of the journal. As far as we can judge, tampering with the corpse was impossible before the opening of the grave and during the manipulation of the remains.

2.2. Genetic identification

Genetic analyses were performed on a bone fragment and a tooth collected during exhumation. The material from the exhumation was ground and prepared by drilling at low speed. DNA was then extracted using a phenol/chloroform protocol. Identical nuclear DNA (nDNA) profiles comprising 15 and 13 loci (NGM Select kit from Life Technologies) were retrieved from the bone fragment and the tooth, respectively. Those nDNA profiles corresponded to those previously obtained from the belongings of Yasser Arafat [5].

2.3. Toxicological screening

We selected four human remains sampled during the exhumation for systematic toxicological analysis, according to international recommendations [6]. Gas chromatography coupled to mass spectrometry (GC-MS) was used for the detection and identification of compounds. The specimens were diluted into methanol before GC-MS analyses (Agilent 5973N). Specimens were also analyzed after acetylation. Details of the procedure are given in the SI.

2.4. ^{210}Po determination

To obtain a high activity, which is necessary in case of poisoning, ^{210}Po is produced artificially by irradiating a ^{209}Bi target with neutrons in a nuclear reactor. However, ^{210}Po is also the decay product of ^{210}Pb ($T_{1/2} = 22$ y), a naturally-occurring radionuclide which is the result of the decay of the natural radioactive gas ^{222}Rn in the ^{238}U decay chain. When ^{210}Pb contaminates a sample, ^{210}Po will accompany it with a similar activity after about 2 years as a radioactive secular equilibrium establishes between both radionuclides. In this case, ^{210}Po is said to be supported by ^{210}Pb . In this sense supported ^{210}Po is apparently of natural origin. In Yasser Arafat's case, the presence of natural

^{210}Po and ^{210}Pb will possibly mask the presence of artificial ^{210}Po , which – if present as a poisoning material at the time of death – would have decreased by more than two million by the time of exhumation, due to radioactive decay (number of ^{210}Po elapsed half-lives of 21). The main problem for determining the level of artificial ^{210}Po in Yasser Arafat's remains, buried eight years earlier, is the potential presence of diagenetic ^{210}Pb and ^{210}Po . The diagenetic contribution of ^{210}Pb to the total activity of ^{210}Pb is the contribution that is not the consequence of biological uptake during life time. The diagenetic activity is solely derived from accumulation of contaminants from the burial environment. If diagenesis is present, it will yield a radionuclide activity that is in excess of the bone's biogenically derived activity. Therefore, solubility profiling was used to remove diagenetic contaminants, after residual tissue extraction using a basic solution of 1 M NaOH and mineralization in 10% oxygenated water in a pressurized microwave digester (Ultraclave IV, Milestone, Germany). Solubility profiling is based on the differential solubility of bone hydroxyl-apatite from biogenic or diagenetic origin [7]. A soft acidic buffer (10 ml, ammonium acetate 0.2 M at pH 4.5) was used to remove layers of potentially contaminated bone hydroxyl-apatite (1.0 g) in six successive washings. The washing time was 5 min each in an ultrasonic bath, afterwards the bone matrix was totally dissolved in 1 M HCl. After six washings, about 10% of the mass of the bone was removed.

^{210}Po was spontaneously deposited on a silver disk, using its specific electrochemical properties. Then the disc was measured using alpha spectrometry on a PIPS detector (Canberra Alpha Analyst, France), using a ^{209}Po tracer as an internal standard [4]. To quantify ^{210}Pb activity, gamma spectrometric measurements were performed on several grave specimens (soil, bone and shroud) using a Canberra p-type HPGe well detector (GCW4523, Canberra, France) in a 4 ml well-geometry. Typically, ^{210}Pb can be quantified using gamma-spectrometry if the activity of the sample is above 0.1 Bq. For a lower activity level, determining the ^{210}Pb was carried out by separating lead from polonium on a strongly basic resin (Dowex AG1 × 8, Bio-Rad) because $[\text{PoCl}_6]^{2-}$ anion is extracted on the column, while Pb^{2+} is not. Then, polonium-free ^{210}Pb was left to rest for at least three months to allow the secular equilibrium to partially re-establish. After a three month period, ^{210}Po activity reaches 36% of the initial ^{210}Pb activity and was measured using alpha spectrometry as described previously.

Several studies dating back to 1963 were used to obtain a dataset of ^{210}Po reference concentrations in human bones [3,4,8–11]. For statistics, these reference values were separated into two sub-sets, the first one containing the ^{210}Po data from autopsy ($n = 95$) and the second one containing ^{210}Po data from bones sampled after exhumation or found in the environment, e.g. buried in soil, coming from forensic cases ($n = 36$). We compared these datasets to the dataset of ^{210}Po values found in Yasser Arafat bones ($n = 16$).

Unfortunately, an international inter-laboratories comparison for ^{210}Po determination in bone samples does not exist. Thus, the quality control was done through the participation to several international inter-laboratories exercises on ^{210}Po determination in urine samples organized by the PROCORAD association [12], using a somewhat similar procedure to the one described above (2008–2011, $n = 5$; average bias: 4.2%).

2.5. ^{210}Pb impurity: calculation and analysis

To check for ^{210}Pb impurity in ^{210}Po made by irradiating a ^{209}Bi target, a 3 MBq ^{210}Po source (certificate n° 9031-OL-501/13) was bought from the Czech Metrology Institute. Polonium was separated from lead to authenticate the presence of ^{210}Pb as an impurity. ^{210}Pb was measured using gamma-spectrometry

both before and after chemical separation and its presence confirmed by proportional counting of its short half-life (5.01 d) daughter product ^{210}Bi (Tennelec LB4100w). We also separated the lead from four bone specimens, two soils and a scalp subsample to measure the ratio of stable lead $^{207}\text{Pb}/^{206}\text{Pb}$ by mass spectrometry (Element 2, Thermo Scientific), with an accuracy better than 0.1% [13]. The rationale for this measurement was that ^{206}Pb is also the daughter product of ^{210}Po , thus the past presence of a high level of ^{210}Po will yield a lower $^{207}\text{Pb}/^{206}\text{Pb}$ ratio after decay.

2.6. Biokinetic calculation

The systemic biokinetic model of polonium proposed by Legett and Eckerman [14] was implemented in the simulation modeling tool Ecolego [15] and in SAAM II [16] in order to calculate the typical retention of ^{210}Po and ^{210}Pb in organs and tissues in case of intake. Since ingestion is the most probable route of intake for poisoning, the systemic biokinetic model was coupled to the human alimentary tract model as described in ICRP Publication 100 [17]. Absorption of ^{210}Po is assumed to occur exclusively from the small intestine and is characterized by $f_1 = 0.1$ for inorganic form.

Further details of the radiometric, toxicological, genetic and statistical tests, as well as the exhumation procedure and biokinetic calculation procedure can be found in SI.

2.7. Bayesian analysis

Statistical Bayesian analysis is well suited to coherently combine evidence from various origins, in our case medical records, toxicological and radiotoxicology measurements, as well as personal judgements of probability [18]. It fits the goals of the present forensic expert report, which was to estimate the probability of occurrence of a unique event and to evaluate all the evidence in the light of two alternative hypotheses: H_0 Mr Arafat has not been poisoned by ^{210}Po ; H_1 Mr Arafat has been poisoned by ^{210}Po . It was not our task to give an estimate of the probability of H_1 , which contains too many elements that are out of our scope. Our task was to evaluate the likelihood ratio (LR):

$$\text{LR} = \frac{P(E|H_1)}{P(E|H_0)}$$

where $P(E|H_1)$ is the probability of observing a given evidence E if H_1 is true and $P(E|H_0)$ is the probability of observing a given evidence E if H_0 is true. We cannot overemphasize that $P(E|H_1)$ is not equal to $P(H_1|E)$. The former is the probability of observing a given evidence E if Mr Arafat has been poisoned by polonium, whereas the latter is the probability that Mr Arafat has been poisoned by polonium if we observe evidence E.

The likelihood ratio LR measures the relative strength of support which evidence E gives to H_1 . One of the main advantages of the LR is that it can easily be updated with new evidence: the updated LR is simply the previous LR multiplied by LR associated with the new evidence.

3. Results

Before presenting and discussing the results of our analyses carried out on Yasser Arafat's remains, it is important to mention that in a previous study [5], toxicological tests on Yasser Arafat's belongings remained negative with only the patient's medication and metabolites identified, but that ^{210}Po tests were positive on some specimens, particularly on a possible urine stain on his underwear (Fig. 1).

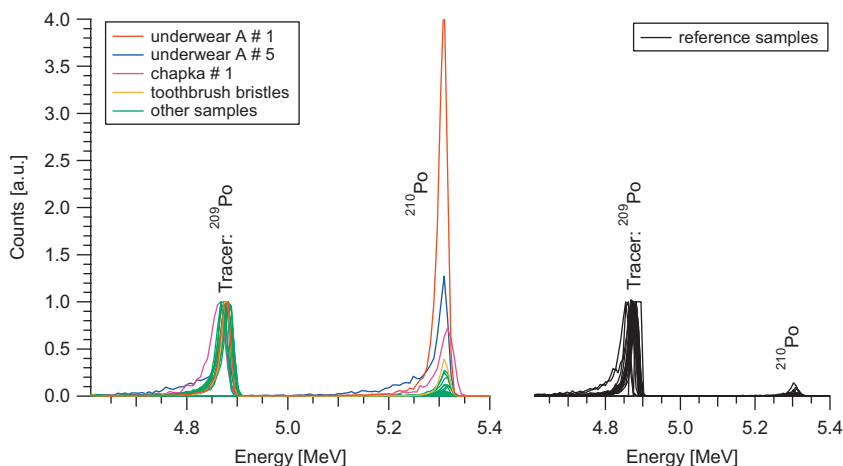


Fig. 1. Polonium alpha spectra of Yasser Arafat's belongings visually stained by biological fluids (left) and reference samples (right). Reference samples included belongings from Yasser Arafat that had not been worn and fabric samples from some IRA collaborators kept in an attic in plastic bags for 10 years. Spectra are normalized to the internal tracer ^{209}Po (50.0 ± 1.0 mBq).

Statistics revealed strong differences between the activities of Yasser Arafat's worn belongings and Yasser Arafat's unworn belongings (p -value $< 1\%$) and between Yasser Arafat's worn belongings and IRA reference fabrics (p -value $< 1\%$). Conversely, no statistical difference was found between Yasser Arafat's unworn belongings (internal references) and our own reference fabrics. Interestingly, 42% of the ^{210}Po from the most contaminated sample was supported by ^{210}Pb . Full results of the ^{210}Po and ^{210}Pb measurements in the belongings can be found in SI of Froidevaux et al. [5].

These initial findings prompted the exhumation of Yasser Arafat's remains for further toxicological analyses. Genetic identification of the human remains from the grave guaranteed that all the specimens were from Yasser Arafat. Only Arafat's medication and its metabolites were found in the human remains. The activity of the ^{222}Rn gas in the grave was $12,000$ Bq/m³, which is a value not especially elevated (for instance, our own measurements in Switzerland performed with the same instrumentation led to a mean value of $35,000$ Bq/m³ on the Swiss Plateau and $90,000$ Bq/m³ in the Jura Mountains [19]). This level validates the comparison of the activities of Yasser Arafat's remains with the activities of bones from other exhumations. Surface activity (mBq/cm²) was determined in three soil specimens, in six shroud fragments, in one scalp fragment and two fragments of a flat bone (iliac). One of the soil specimens was sampled below the abdomen cavity; it contained 42% relative humidity (H_r) and had a strong black colour compared to 26% H_r for a red soil sampled far from the corpse (reference soil from the front right corner of the tomb). Thus the stained soil is believed to contain decayed body fluids. Its surface activity was 30 ± 4 mBq/cm² whereas the surface activity of the reference soil was only 1.7 ± 0.3 mBq/cm². The surface activities of the shroud and the reference soil (located away from the corpse) can be considered as representative of samples not contaminated by the corpse and possibly only exposed to radon decay product. The mean activity was 3.9 ± 0.7 mBq/cm². Wax (decomposed tissues, from 0.5 to 1 mm thickness) was carefully removed from a surface of the iliac flat bone and its ^{210}Po activity determined. Wax is known to be a good interceptor of airborne radioactive particles and paraffin wax is used near nuclear installations to check for radioactive aerosols. Therefore any contamination of the iliac by ^{222}Rn progeny (^{210}Pb and ^{210}Po) should be concentrated in the wax coating the bone.

The soil specimen located left from the corpse was not statistically different, whereas the surface activities of the iliac

crest waxed tissue, the scalp and the black stained soil located under the abdominal cavity were all significantly higher (p -value $< 10^{-5}$).

Results are presented in Fig. 2.

^{210}Po and ^{210}Pb were measured in 16 fragments of bone and results showed that the ^{210}Po was supported by ^{210}Pb , e.g. the activity of ^{210}Pb was at least equivalent to the activity of ^{210}Po . Nevertheless, some of Arafat's bone fragments contained much higher (up to 20 times) ^{210}Po and ^{210}Pb activities than the reference bones (Fig. 3). Furthermore, the isotopic ratio of stable $^{207}\text{Pb}/^{206}\text{Pb}$ was lower in the rib and scalp specimens, which were precisely the specimens with the highest ^{210}Po activity (see SI for details).

The Yasser Arafat results were compared to previously published autopsy data (4; 8–11). The ^{210}Po activities differed significantly with 8 out of 16 ^{210}Po values with a p -value lower than 1%. To take into account the possibility of diagenesis, even after solubility profiling, the Yasser Arafat dataset was further compared to the exhumation dataset [3,20,21]. The ^{210}Po activities differed even more significantly, with 15 out of 16 ^{210}Po activities having a p -value lower than 1%.

In addition, several sub-specimens of the iliac crest were measured. The ^{210}Po activities were found to increase from the inner part to the outer part of the iliac bone (Fig. 4). In all of the iliac sub-specimens, ^{210}Po activities were also supported by ^{210}Pb . The results of all the ^{210}Po and ^{210}Pb measurements carried out in specimens taken from the grave can be found in Table SI-2.

Since ^{210}Po was supported by ^{210}Pb in all of the measured specimens, it is possible that the presence of ^{210}Po was natural, in spite of all the precautions taken to decontaminate the bones. Nevertheless, diagenesis in Yasser Arafat's remains should be lower compared to other exhumed remains because his body was not buried. It simply rested on a thin layer of 10 cm of soil, wrapped in a shroud at the time of inhumation. Thus bone specimens were not spoiled by soil particles and the corpse was protected by the shroud, at least during the time necessary for the shroud to decompose. Another explanation could be that ^{210}Pb was present as a by-product of ^{210}Po production by neutron irradiation, and not separated from polonium due to the formation of a volatile lead polonide, PbPo [22,23]. Calculations carried out by the Paul Scherrer Institute, Switzerland, showed that the production of some ^{210}Pb during ^{209}Bi activation by neutrons is possible, but with a very low $^{210}\text{Pb}/^{210}\text{Po}$ activity ratio of around 10^{-12} , depending on the ^{208}Pb impurity into the ^{209}Bi target taken into account. Nevertheless, an impurity of ^{210}Pb at a much higher level was

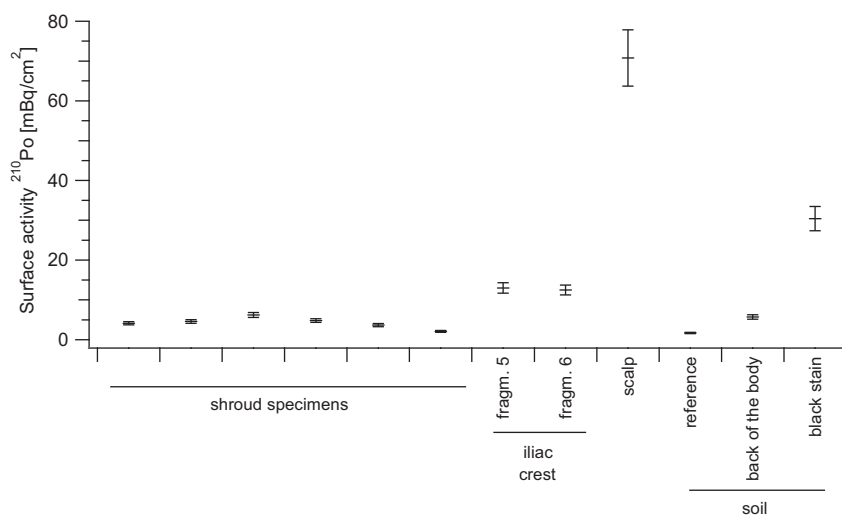


Fig. 2. Surface activity of ^{210}Po (mBq/cm²) of some specimens sampled from the grave during the exhumation. Deposition on the iliac crest was calculated using the wax coating activity and the surface of the flat bone fragment.

found in a commercial source of ^{210}Po of 3 MBq (see SI for details). The results of the measurements show that ^{210}Pb was present as an impurity with an activity ratio of $^{210}\text{Pb}/^{210}\text{Po}$ of 1.5×10^{-7} . Only an elapsed time of 2.5 years is needed to reach an impurity factor of

10^{-5} , starting from the commercial source that was investigated. Taking into account the difference in half-life between ^{210}Po (138 d) and ^{210}Pb (22 y), ^{210}Pb rapidly becomes an impurity that might explain the ^{210}Pb and ^{210}Po activity levels found in Yasser

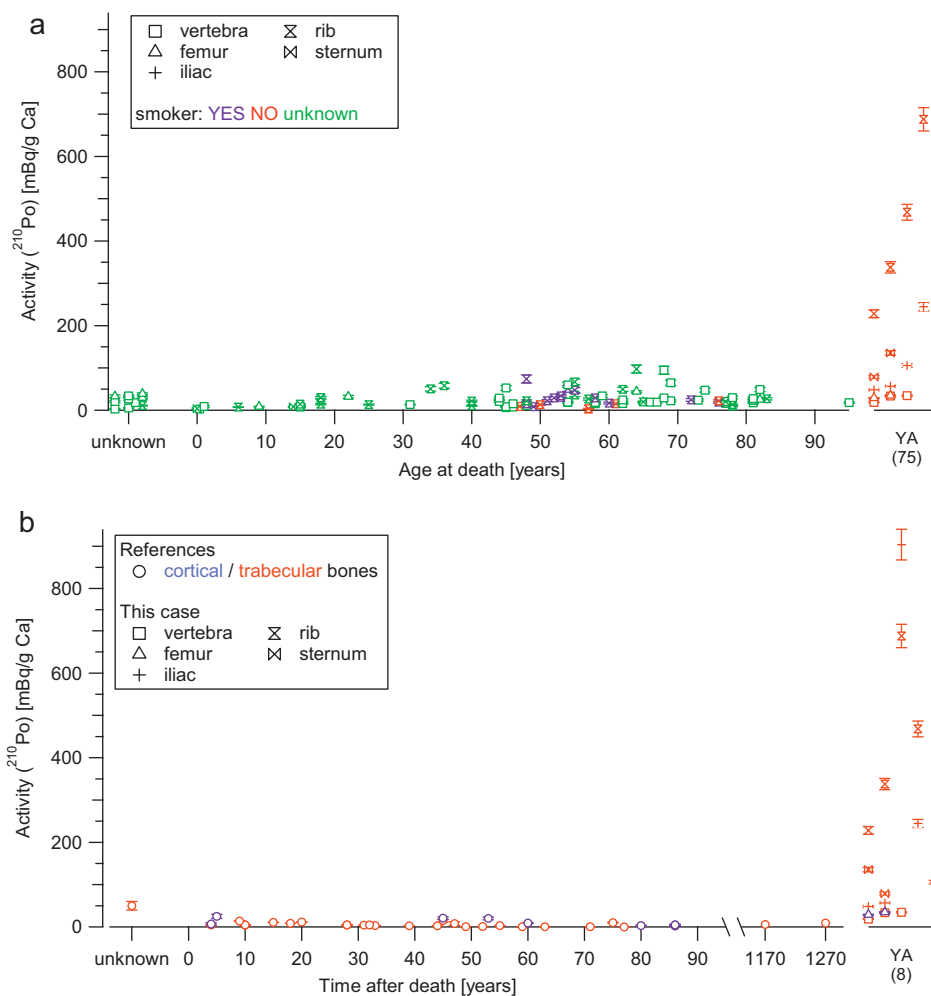


Fig. 3. (a) ^{210}Po activities (mBq/g Ca) of all specimens of bone from Yasser Arafat (right) compared to references activities from the autopsy dataset, reported versus the age at death. (b) ^{210}Po activities (mBq/g Ca) of all specimens of bone from Yasser Arafat (right) compared to references activities from the forensic dataset, reported versus the known or estimated time since death.

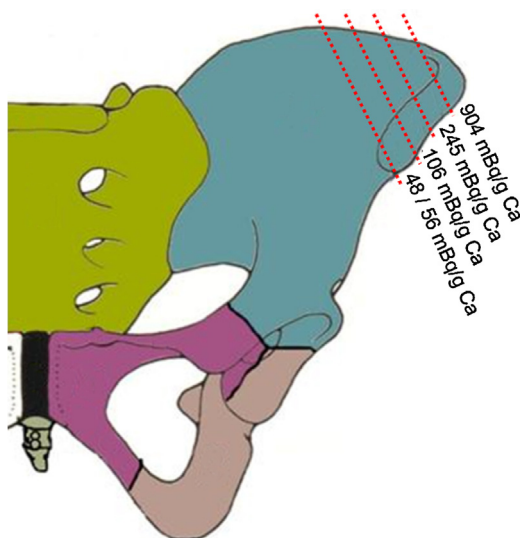


Fig. 4. Locations and ^{210}Po activities in the iliac crest bone.

Arafat's remains. Additionally, ^{210}Pb is a bone-seeking radioelement that will accumulate in the skeleton ten times more compared to ^{210}Po [24]. A calculation using a scenario where a lethal activity of 1 GBq of ^{210}Po was ingested with a ^{210}Pb impurity ratio of 10^{-7} , 10^{-6} and 10^{-5} is presented in Fig. 5.

4. Discussion

4.1. Radioanalytical results

The time elapsed since Yasser Arafat's death and this study is eight years. During these eight years, artificial ^{210}Po in Yasser Arafat, if present at death, would have decayed by about two million (number of elapsed ^{210}Po half-lives of 21). This is the major limitation of our overall forensic report because by the time we performed our measurements any residual artificial ^{210}Po has possibly reached the natural level of activity found in human bones. Nevertheless, a significant activity of ^{210}Po was found in Yasser Arafat's belongings and remains. Certain bone specimens, such as rib, iliac and sternum, had much higher ^{210}Po activity compared to the published literature on this subject. Thus the ^{210}Po activities found in Yasser Arafat's remains do not fall within a normal range of activity for unexposed persons. These findings are in accordance with the unexpected level of ^{210}Po previously found

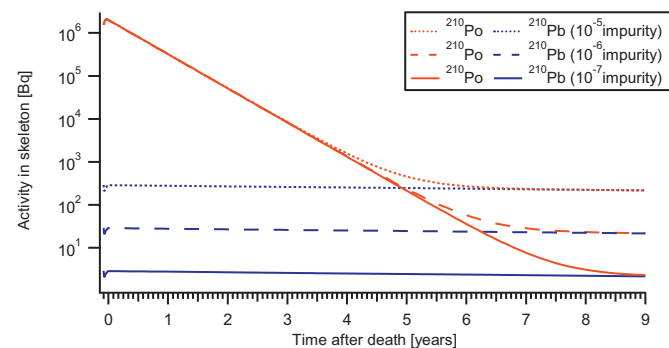


Fig. 5. Total activity in the skeleton following a ^{210}Po intake of 1 GBq. Three scenarios were computed with impurities of ^{210}Pb in the source of 0.1 kBq (impurity factor of 10^{-7}), 1 kBq (10^{-6}) and 10 kBq (10^{-5}). The activities of ^{210}Po and ^{210}Pb reach equilibrium after about 8.5 years, 7.1 years and 6 years, respectively.

in some of Yasser Arafat's belongings [5]. However, ^{210}Po could not be attributed unequivocally to the ingestion of an artificial source of polonium given that it was supported by the same activity of ^{210}Pb . In this respect, ^{210}Po may appear natural and its presence explained as the consequence of ^{222}Rn decay within the tomb.

We ruled out this hypothesis as an explanation for the apparent secular equilibrium between ^{210}Po and ^{210}Pb because a very careful decontamination process based on solubility profiling of the bone matrix was carried out. During this process, 10% of the mass of the bone is removed, to expose only inner, and therefore contamination-free, surfaces. Additionally, most of the bones were still covered by a thin layer of wax that was mechanically and chemically removed before solubility profiling. This means that the wax should have been the receptor of diagenetic contamination rather than the bone structure. In our laboratory, 15 cases of forensic interest were treated similarly in a previous study and revealed no such ^{210}Po and ^{210}Pb activities [3] as those found in Yasser Arafat's rib, sternum and iliac. In addition, the dataset from Swift [20] and Ziad et al. [21] contain ^{210}Po measurements of bones from exhumation that were only decontaminated mechanically, mainly by abrasion with sand paper; the maximum ^{210}Po activity measured was 15 mBq/g Ca, a value far below those measured in Yasser Arafat's rib, sternum and iliac. In a prior study, we used a dataset of 20 exhumed vertebrae which had been buried for 20 years, to test the level of diagenesis in the trabecular bones in contact with soil particles [4]. Without decontamination, the maximum activity found in bone with strong diagenetic contamination was 300 mBq/g Ca, an activity which lowered further to 36 mBq/g Ca after 6 washings with acetate buffer. Once again, no ^{210}Po activity such as those measured in Yasser Arafat's remains was found. Another finding points to a biogenic origin of ^{210}Po and ^{210}Pb ; strong heterogeneity was found in the activities measured along an inner-outer transect in the iliac bone, with a steady increase in activity from the inner to the outer part (Fig. 4). Additionally, only highly vascularised bones such as the iliac, rib and sternum contained very significant ^{210}Pb – ^{210}Po activity, while cortical bone such as the femur had somewhat close to background activity. This finding is not compatible with a diagenetic origin of ^{210}Pb – ^{210}Po but matches a distribution pattern coherent with an incorporation of a bone-seeking element shortly before death [24].

While we do not put emphasis on the results of the stable $^{207}\text{Pb}/^{206}\text{Pb}$ ratio because of large uncertainties in the measurement, the trend of low ratio values for the two specimens with the highest measured ^{210}Po activities might indicate the presence of a high ^{210}Po level in the past.

Additionally, if the ^{210}Po and ^{210}Pb measured in the body were of a diagenetic origin, similar surface activities on the reference soil and the shroud would be expected on the one hand, and on the black stained soil and the scalp on the other hand. This was not the case and the latter values are significantly higher. Therefore, and knowing that the activity concentration of ^{222}Rn measured before opening the tomb was relatively low for a soil, we are confident that the ^{210}Po and ^{210}Pb measured in this study are of biogenic origin.

Nevertheless, the question remains regarding the provenance of ^{210}Pb in Yasser Arafat's bones. We measured a commercial ^{210}Po source of 3 MBq and found it to contain a significant activity of ^{210}Pb impurity able to explain the high ^{210}Po and ^{210}Pb activities found in Yasser Arafat's remains, as well as the presence of a secular equilibrium between ^{210}Po and ^{210}Pb eight years after death. Furthermore, ^{210}Pb is a bone-seeker and has a long half-life of 22 years. Its presence as an impurity in a ^{210}Po ingested source will leave a ^{210}Pb – ^{210}Po trace for much longer than ^{210}Po alone, as was demonstrated using a biokinetic calculation (Fig. 5). Additionally, there is strong evidence that ^{210}Pb may be a significant impurity in a ^{210}Po source made by irradiation of ^{209}Bi .

4.2. Medical file

As already mentioned, the assassination of Alexander Litvinenko represents the only openly documented ^{210}Po poisoning case. Although it has not been described in the conventional scientific literature, the evidence from the Litvinenko case have been made public on the internet [25]. The inquiry showed that Mr Litvinenko's contamination probably resulted from one substantial intake, although the results of autoradiography measurements of alpha emitter performed on his hair suggest that a much smaller contamination may have occurred a couple of days earlier [26,27]. The first reported symptoms were vomiting and diarrhoea, together with abdominal pain followed by alopecia and myelosuppression. Then multiple organ failure, including kidney and liver deficiencies, led to his death.

Comparatively, Yasser Arafat's medical records essentially showed gastrointestinal symptoms at the onset, followed by liver and renal damage and ended with multiple organ failure. Multiple organ failure is, however, a non-specific final issue that can frequently not be attributed to a specific triggering event. Although mild myelodysplastic changes of the bone marrow were found about two weeks after the first symptoms, myelosuppression and alopecia were not observed in Yasser Arafat. At first glance, this striking difference between the two medical records suggests polonium poisoning in the case of Yasser Arafat must be ruled out. However, before drawing a definite conclusion, it is important to take into account the difference between external irradiation and radionuclide intake, and how the time delivery-scheme of intake could affect the observed symptoms.

Ionizing radiations, including gamma rays and alpha particles are known to damage biological molecules, including DNA. ^{210}Po is an alpha emitter, which is particularly destructive at the cellular level as alpha particles deposit all their energy within tens of micrometers. Therefore, radiological damages induced by ^{210}Po are not uniform within the whole body, because they are directly related to the location of the individual polonium atoms, which is defined by their specific biokinetic. This is very different than external irradiation with penetrating radiation, like photons or neutrons that tend to produce relatively homogenous dose deposition within all exposed organs. While persons exposed to high doses of external irradiation tend to develop haematopoietic, gastrointestinal, cardiovascular, central nervous system and skin reactions, the reaction following the intake of alpha-emitting nuclides may be very different and is much less documented. In the case of ^{210}Po intake, the toxicity is influenced by the specific tissue sensitivities and the accumulation of the radionuclide in the different organs.

After ingestion of ^{210}Po , it is considered that the gut is the primary target for the initiation of prodromal responses, including vomiting and diarrhoea [28]. The toxic substance is then absorbed into the blood ($f_1 = 10\%$) and redistributed to the organs where it can be incorporated and distributed, mainly to the liver and the kidneys [14,29].

Tissue effects depend on the organ and have a dose threshold that varies from person to person, and below which nothing is detectable without conducting a clinical test. This means that depending on the amount of intake and its time delivery-scheme the organs that show an effect could vary. For ^{210}Po , the available animal and human data indicate that a sufficiently high intake can lead to death after multiple organ failure. For lower intakes, animal studies have shown protracted effects resulting only in kidney damage and then death [27]. Other animal studies have shown that low intakes did not provoke haematological abnormalities and that only mild kidney lesions could be noticed [29,30]. The same studies also showed that the initially observed damage to the bone marrow could be followed by an active regeneration.

All these considerations allow us now to examine the plausibility of observing the reported symptoms of Mr Arafat in light of ^{210}Po poisoning. In this forensic context, we considered different possible time delivery-schemes. We will therefore discuss in the next paragraphs two situations: one in which a single high activity was ingested and another in which smaller activities were ingested repeatedly.

The fact that myelosuppression and hair loss are missing in Mr Arafat's case does not support a single high activity intake of ^{210}Po . However, side-effects observed with high activities injected or ingested in nuclear medicine therapy include nausea, vomiting, fatigue and abdominal pain, but less frequently hair loss. Furthermore, myelosuppression varies greatly among patients treated either with beta-emitters [31] or alpha-emitters [32]. As a matter of fact, the extent of myelosuppression to be expected following intakes of radionuclides will differ according to their chemical and physical characteristics. For example, the effect of alpha particles emitted from radium isotopes deposited in bone mineral will be limited mainly to peripheral marrow and other parts of the marrow will be unaffected. Recent treatments with bone-seeking alpha-emitters such as ^{223}Ra confirmed that myelosuppression was then minimal [32,33]. According to the ICRP intake model, ^{210}Po tends to be deposited on the bone surface during the first month after intake. Because of the short range of alpha particles, the dose delivered from the bone surface to the active marrow is highly heterogeneous and large fractions of the active marrow are spared [33]. The uptake of ^{210}Po on the bone surface is thus not expected to systematically cause severe myelosuppression. It is then only the amount of ^{210}Po absorbed into the blood that contributes to the bone marrow dose. All this considered, the absence of myelosuppression and hair loss does not support a single high intake of ^{210}Po but does not exclude the possibility.

In the scenario of repeated intakes of small ^{210}Po activity, we can picture that the "last straw" triggered the clinical symptoms, which were subclinical after previous intakes. In Yasser Arafat's case, low marrow cellularity (i.e. increased adipocyte concentration) associated with aging might also have attenuated the myelosuppression. Indeed, as marrow cellularity decreases, alpha particles increasingly encounter adipocytes and the energy deposited into active marrow is thus decreased [34]. This could potentially reduce myelosuppression in the elderly. It is also possible that the intake could be too low to damage the red bone marrow or that the transiting damage could recover during the interval between two successive intakes as it was observed in animal studies [30]. The same argument could possibly explain the absence of hair loss through recovery of the skin basal cells.

As already mentioned, the alimentary tract is considered to be the primary radiation target of ^{210}Po involving the release of a neurotransmitter from intestinal cells that activates the brain-vomiting centre [26]. This is further supported by the fact that the present biokinetic model probably underestimates the dose as it does not take into account the possibility of retention in the gastrointestinal tracts [28]. This explains the presence of vomiting and diarrhea in the Litvinenko case. For Yasser Arafat, no explanations for these observed symptoms were found despite very extensive clinical investigations. Harrison et al. [28] also reported results from a rat study suggesting that damage to the gut mucosa was the possible cause of death in a case of ingestion of ^{210}Po . After ingestion of ^{210}Po , the gastrointestinal syndrome, associated with multiple organ failure, could therefore be a predominant cause of death [35,36].

4.3. Russian forensic expert report

Two other teams also took part in the exhumation of Yasser Arafat and analyzed similar samples: a French team commissioned

by the French justice department and a Russian team commissioned by the Palestinian Authority. Contrary to the French, the Russians published their results [37]. Their analytical results were very similar to our measurements. They also measured bone activities of ^{210}Po and ^{210}Pb at equilibrium that were much higher than normal. They tested two hypotheses: contamination by radon in the tomb and ingestion of a ^{210}Pb source shortly before death. They rejected both hypotheses and concluded that “unfortunately, it is not possible to state clearly the cause of the ^{210}Pb radionuclide presence in the samples only on the basis of the physical research results”. Concerning the medical file, they considered that ^{210}Po poisoning should have led to a full spectrum of acute radiation syndrome. Specifically, they were expecting myelosuppression and hair loss. They did not take into account our measurements on the personal belongings [5] and concluded that “a direct causal link between the presence of high content of [^{210}Po and ^{210}Pb] in the remains of the deceased and his death should be excluded”.

4.4. Bayesian analysis

The evidences gathered during this expert report are not clear-cut: we cannot exclude ^{210}Po as a cause of death, but we cannot be sure that ^{210}Po was the cause of death. We have three main contributions to take into account for calculating LR: the measurements performed on the belongings, the measurements performed on the exhumed body remains, and the analysis of the medical files. We estimate each contribution separately.

The measurements performed on the personal effects showed large quantities of unsupported ^{210}Po associated with the presence of biological fluids. Although this has been published for two years [5], no alternative explanation to polonium poisoning has been proposed.

The measurements performed on the remains showed a high quantity of supported ^{210}Po but were about 20 times higher than all other exhumed cadavers documented in the scientific literature. These high activities cannot be explained by the presence of radon in the tomb but are coherent with the ingestion of a ^{210}Po source containing an impurity of ^{210}Pb akin to what we measured in a commercial source.

Concerning the medical file, the situation is similar. Yasser Arafat did not show all possible symptoms observed in the case of acute radiation syndrome. In particular, no myelosuppression and no hair loss were documented. In a forensic expert report, we have to factor in the variability of reactions that are probably present. For instance, Mr Arafat was 32 years older than Mr Litvinenko at the time of their deaths. Mr Litvinenko lost his hair and showed a clear myelosuppression, but, as discussed before, this is not always documented in radiation therapy patients of nuclear medicine. If we open the range of possible poisoning scenarios, we should also consider possible repeated smaller intakes. As mentioned above, this type of scenario could lead to gastro-intestinal symptoms that could appear once a certain threshold has been exceeded and then develop into multiple organ failure.

We can now process all this information using a Bayesian analysis, and estimate the LRs associated with each piece of evidence. We estimated that the LR of high activity of unsupported ^{210}Po in the personal belongings is larger than one: in other words, it is more likely to observe unsupported ^{210}Po in the biological stains if Mr Arafat had been poisoned than if he had not. For the high activities of supported ^{210}Po found in the remains, the LR is also larger than one because, to our knowledge, no documented cadaver has been measured with such an activity. Furthermore, no plausible alternative explanation has been proposed and the presence of a small impurity of ^{210}Pb in a ^{210}Po source could lead to what has been observed in Mr Arafat's bones. The medical file analysis points toward the opposite, because of the differences

between Mr Arafat and Mr Litvinenko. Consequently, we estimated that the corresponding LR is smaller than one. However, LR is certainly not zero because a repeated series of small intakes of ^{210}Po or a specific weaker cellular reaction of Mr Arafat could also explain the observed symptoms and, mostly, because the Percy Hospital physicians did not ultimately identify the cause of Yasser Arafat's death.

Putting all of this together, we estimate that the LR associated with the medical file is not small enough to compensate the relatively large LRs associated with the measurements on Mr Arafat's personal belongings and remains. Therefore, we have to deduce that our radiotoxicology analyses and the observed medical symptoms support the proposition that Mr Arafat was poisoned by ^{210}Po . This support is maybe not strong, but certainly not slight.

5. Conclusions

Despite extensive clinical investigations, the cause of the gastrointestinal symptoms followed by multiple organ failure developed by Yasser Arafat was not determined at time of his death. Our study presents analytical results that support the hypothesis of ^{210}Po poisoning essentially on the basis of unexplained ^{210}Po activities found in Yasser Arafat's belongings worn shortly before his death and on unexplained ^{210}Pb and ^{210}Po activities found in his remains.

Alexander Litvinenko's case is at this time the only documented case related to acute radiation syndrome following upon ^{210}Po malicious administration. The comparison of these two cases showed clinical similarities except for alopecia and myelosuppression experienced by Alexander Litvinenko. Nevertheless, this difference is not an argument to exclude with sufficient certitude the hypothesis of ^{210}Po poisoning if we consider that the administration scheme could have been different in the two cases: an acute poisoning by administration of a substantial dose versus poisoning by the repetition of smaller doses. Moreover, it should also be taken into account all possible interfering factors such as age, previous health status and genetic predisposition—all of which could lead to different symptoms.

In conclusion, even if our findings reasonably support the hypothesis of ^{210}Po poisoning, Yasser Arafat's cause of death will probably remain a cold-case.

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There are no financial or other relations that could lead to a conflict of interest. However, the costs of the analyses were covered in equal part by Mrs. Suha Arafat and the Palestinian Authority (PA). In addition, due to security concerns, the PA accommodated the Swiss team during its stay in Ramallah. Neither Mrs. Suha Arafat, nor the PA had a role in study design, data gathering, data analysis, data interpretation, or writing of the report. All the other costs of the expertise were covered internally by the Lausanne University Hospital. The Expert Forensic Report concerning the Late President Arafat that we wrote in our quality of Swiss Experts Team was handed jointly to both Mrs. Suha Arafat (represented by her legal counsel) and to the PA officials during a meeting in Geneva, November 5th, 2013. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.forsciint.2015.09.019>.

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