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THYROID DOSES TO FRENCH POLYNESIANS RESULTING FROM ATMOSPHERIC NUCLEAR WEAPONS TESTS: ESTIMATES BASED ON RADIATION MEASUREMENTS AND POPULATION LIFESTYLE DATA

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Abstract

Thyroid doses were estimated for the subjects of a population-based case-control study of thyroid cancer in a population exposed to fallout after atmospheric nuclear weapons tests conducted in French Polynesia between 1966 and 1974. Thyroid doses due to (i) intake of ^{131}I and of short-lived radioiodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te, (ii) external irradiation from gamma-emitting radionuclides deposited on the ground, and (iii) ingestion of long-lived ^{137}Cs with foodstuffs were reconstructed for each study subject. The dosimetry model that had been used in 2008 in Phase I of the study was substantially improved with (i) results of radiation monitoring of the environment and foodstuffs, which became available in 2013 for public access, and (ii) historical data on population lifestyle related to the period of the tests, which were collected in 2016–2017 using focus-group discussions and key informant interviews. The mean thyroid dose among the study subjects was found to be around 5 mGy while the highest dose was estimated to be around 36

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mGy. Doses from ^{131}I intake ranged up to 27 mGy, while those from intake of short-lived iodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te ranged up to 14 mGy. Thyroid doses from external exposure ranged up to 6 mGy and those from internal exposure due to ^{137}Cs ingestion did not exceed 1 mGy. Intake of ^{131}I was found to be the main pathway for thyroid exposure accounting for 72% of the total dose. Results of this study are being used to evaluate the risk of thyroid cancer among the subjects of the epidemiologic study of thyroid cancer among French Polynesians.

Keywords

atmospheric nuclear weapons test; French Polynesia; thyroid; radiation dose

INTRODUCTION

To evaluate health effects in French Polynesian population exposed to fallout from atmospheric nuclear weapons tests conducted in Mururoa and Fangataufa between 1966 and 1974, the National Institute of Health and Medical Research (Institut National de la Santé et de la Recherche Médicale, INSERM, Paris, France) initiated a population-based case-control study of thyroid cancer. The study consisted of two phases. Phase I included all alive cases of thyroid cancer developed between 1985 and 2003 in persons who were children, adolescents, and young adults at the time of atmospheric nuclear testing. Epidemiological aspects of Phase I and estimates of risk of thyroid cancer were published by de Vathaire et al. (2010). Overall, 602 subjects, both cases and controls, were included in the thyroid cancer radiation-associated risk analysis with thyroid doses calculated in 2008 using the ‘Thyroid Dosimetry 2008 system’ (TD08) (Drozdovitch et al. 2008). In 2014–2017 INSERM undertook Phase II of the epidemiological study, including 348 additional subjects, thus resulting in a total of 950 subjects. Because of deficiencies in TD08, mainly related to limitations in the input data, the dosimetry system was improved for the assessment of thyroid doses for all subjects of the epidemiologic study.

One of the major deficiencies was the limited information on lifestyle in French Polynesia in the 1960s–1970s that was available for TD08. Individual data for each study subject had been collected by means of personal interviews on (i) places of residence in 1966–1974; (ii) consumption rates of various foodstuffs at age 15; (iii) source of drinking water, i.e. individual cistern, communal cistern, other; and (iv) type of residence, i.e. apartment or house. However, important information, needed for precise dose estimation, was missing in the questionnaire; this included; (i) the type of construction materials used to build the residences; (ii) the time spent indoors at different ages and locations; (iii) the consumption rates of foodstuffs by the subjects during infancy and childhood; (iv) the consumption rates of foodstuffs by women (mothers of the study subjects) who were pregnant or lactating during the period of atmospheric testing. To overcome these limitations, a special study was conducted in French Polynesia in 2016–2017 to collect historical behavior and dietary habits of the French Polynesia population in the 1960s–1970s using focus-group discussions and key-informant interviews. Detailed description and results of the focus-group study can be found elsewhere (Drozdovitch et al. 2019a).

Another limitation of TD08 was related to the paucity of radiation measurements that were available for the estimation of the radionuclide deposition densities, and, in turn, of the thyroid doses in TD08. The radiation data for TD08 included mainly the results of measurements of (i) total[9] beta activity in filtered air, (ii) ^{131}I and ^{137}Cs concentrations in cow's milk produced in Tahiti, and (iii) total gamma activity in foodstuffs. These radiation data had been taken from annual reports on radiation monitoring in French Polynesia, which had been sent to the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) Secretariat (RF, 1967, 1969, 1971–1975) by the French Government after each series of tests. However, the results of radiation monitoring were reported only for 9 islands and atolls after some tests. In 2013, the French Ministry of Defense and Veterans Affairs de-classified original reports from the Joint Radiological Safety Service (Service Mixte de Sécurité Radiologique, SMSR) and from the Joint Biological Control Service (Service Mixte de Contrôle Biologique, SMCB), which included detailed results of radiation monitoring of the environment and foodstuffs for 20 islands and atolls in French Polynesia in 1966–1974 (e.g. SMSR (1967, 1969), SMCB (1972, 1973)). The data from these de-classified reports, which were not available for public access at the time of the TD08 assessment, were used in Phase II of the study to estimate the deposition densities of radionuclides following practically each of 41 tests in 49 islands and atolls where the study subjects resided in 1964–1974 (Drozdovitch et al. 2019b).

This paper presents the 'Thyroid Dosimetry 2019 system' (named TD19 here and below), which was to process the input data on population lifestyle and radiation fallout and to estimate the individual thyroid doses received by all study subjects of a case-control study of thyroid cancer in French Polynesia.

MATERIALS AND METHODS

Study population

Table 1 shows the distribution of the study subjects according to year of birth and gender. One hundred-sixteen (14.4% of the total) study subjects are male. Three hundred forty-two study subjects (42.5% of the total) were 7-y old or younger at some point between 2 July 1966 and 14 October 1974 when the nuclear weapons tests were conducted. Ninety-six study subjects (11.9% of the total) were exposed *in utero*. It should be noted that there are two groups of study subjects who were not exposed to fallout from atmospheric nuclear weapons tests: (i) 114 subjects (12.0% of the total) who were born in 1975 or later, and (ii) 32 subjects (3.4% of the total) who were born before 1975 but did not reside in French Polynesia during the period of atmospheric testing. These persons were not considered in the dose reconstruction and, therefore, this paper deals with 804 study subjects (84.6% of the total).

During the atmospheric nuclear weapons testing period, the study subjects resided in 49 islands and atolls (Fig. 1). Among them, 652 of the 804 subjects (81.1% of the total) lived in the most populated Society Islands, including 490 subjects (61.0% of the total) who lived in Tahiti.

Personal interviews

Information on each study subject's whereabouts, type of residence, duration of breastfeeding, diet at adolescence (15-y old) and source of drinking water was collected by means of personal interview in Phase I of the study. For Phase II the questionnaire was improved by the French and U.S. dosimetrists and epidemiologists based on the experience gained from Phase I. The following questions were added to the questionnaire used during Phase II to interview the additional 348 study subjects: (i) construction material of residence and (ii) consumption of leafy vegetables, such as fâfâ (leaves of taro, very similar to spinach), pota (Chinese cabbage), watercress salad, and spinach, which were among the main sources of ^{131}I intake.

Table 2 presents the fractions of consumers and the daily consumption of foodstuffs at age 15 reported by the study subjects: 41% of the study subjects who resided in Tahiti reported consumption of fresh cow's milk, 67% of the study subjects reported consumption of leafy vegetables and the majority of the study subjects (more than 70%) reported consumptions of coco milk, fruits (banana, mango, papaya), root vegetables (manioc, taro, sweet potatoes), meat (poultry, beef) and fish from lagoon.

One hundred thirty-one study subjects (16.3% of the total) were breastfed during atmospheric nuclear weapon testing. One hundred twenty-six study subjects (15.7% of the total) reported that they used family cistern (58 subjects) or communal cistern (68 subjects) as a source of drinking water.

Estimation of individual thyroid doses

Individual thyroid doses were estimated for the study subjects for the time period from 2 July 1966 (date of first test Aldébaran) through 31 December 1974 (last day of the last year of atmospheric testing). The reconstruction of doses was performed blindly regarding the case or control status of the study subject. The following pathways of exposure were considered:

- Inhalation of ^{131}I and of short-lived radioiodine isotopes (^{132}I, ^{133}I and ^{135}I) and radiotellurium (^{132}Te) with contaminated air;
- Ingestion of ^{131}I and of short-lived ^{132}I, ^{133}I, ^{135}I and ^{132}Te with fresh cow's milk (only in Tahiti), leafy vegetables and drinking water;
- External irradiation from radionuclides deposited on the ground and other materials;
- Ingestion of ^{137}Cs with foodstuffs and drinking water.

Fig. 2 shows the scheme of the thyroid dose assessment for the subjects of a case-control study of thyroid cancer in French Polynesia. Table 3 provides information on the radionuclides that were considered in the assessment of the thyroid doses.

As mentioned above, the TD08 model was substantially improved with data on behavior and food consumption of the population in the 1960s–1970s, which was collected in all archipelagos of French Polynesia using focus-group discussions and key-informant interviews (Drozdovitch et al. 2019a). The data collected during the focus-group study were used in TD19 in the following way:

- Information on the consumption of various foodstuffs during only early adolescence at age 15 was collected from the study subjects as many of them were too young at the time of the nuclear tests to recall their consumptions at younger ages. In TD08, the consumption by the study subject of each foodstuff at any age less than 15 was scaled by ratio of consumption at age *k* to consumption at age 15 using the results of a survey conducted by Grouzelle et al. (1985) in 1980−1982 on age-specific diet in Tahiti. However, this survey has two weaknesses: (i) it was done more almost 10 years after the time of nuclear weapon testing, and (ii) it did not include data for locations other than Tahiti. To overcome these limitations, the values of the scaling factor, which is the ratio of the consumption rate at age *k* to the consumption at age 15, were obtained from a focus-group study for children of different ages who resided in different archipelagos in the 1960s−1970s. In the implementation of the dose calculation, individual consumption rates of specific foods at age 15, which were reported during the personal interview by the study subject, were multiplied by the archipelago-specific scaling factors obtained from the focus-group study (Table 4). Details are provided in the section "Estimation of consumption rates at age *k* from the consumption rates reported at age 15".
- Questions on consumption of leafy vegetables, such as fâfâ and watercress salad, which were some of the most important sources of ^{131}I intake with diet, were not included in the questionnaire of Phase I. Information on consumption of fâfâ and watercress salad at different ages in the 1960s−1970s was collected during the focus-group study (Drozdovitch et al. 2019a). Therefore, the missing values of consumption rates of fâfâ and watercress salad by the study subjects included in Phase I were imputed with the mean age-specific consumption rates obtained in the focus-group study.

Another substantial improvement of TD08 relates to the use of data on deposition densities of radionuclides resulting from atmospheric nuclear weapons tests in islands and atolls that were derived from recently de-classified SMSR and SMCB reports (Drozdovitch et al. 2019b). Details are provided in section "Radiation data".

The way individual thyroid doses due to different exposure pathways were estimated for the study subjects is described in the following sections. Summary of parameters of the dosimetry model to calculate doses is given in Appendix.

Thyroid dose due to inhalation

The internal thyroid dose to a study subject of age *k* arising from inhalation of air contaminated with radioiodine isotopes (^{131}I, ^{132}I, ^{133}I, ^{135}I) and ^{132}Te, D_k^{inh}(mGy), was calculated as:

$$D_k^{inh} = V_k^{air} \cdot RF^{air} \cdot \sum_i TIA_i^{air} \cdot DC_{i,k}^{inh} \quad (1)$$

where V_k^{air} is the age-dependent breathing rate of the study subject (m^3 s^{-1}) (ICRP 2002); RF^{air} is the reduction factor associated with indoor occupancy (unitless). As buildings in French Polynesia are very open for outdoor air circulation, RF^{air}=1 was applied in the calculations; TIA_i^{air} is the time-integrated concentration of radionuclide *i* in air (Bq s m^{-3}); $DC_{i,k}^{inh}$ is the age-dependent inhalation dose coefficient for the thyroid, i.e. the thyroid dose due to inhalation of unit activity of radionuclide *i* by a study subject of age *k* (mGy Bq^{-1}) (ICRP 1995).

Values of total time-integrated concentration in air were taken from SMSR reports or estimated as described by Drozdovitch et al. (2019b). The value of the time-integrated concentration in air of specific radionuclide *i* was derived from the radionuclide mix at time of arrival of fallout (TOA) calculated by Hicks (1981) assuming that the radionuclide composition in filtered air was the same as that in the activity deposited on the ground. If the total deposition density was measured, an estimate of the time-integrated concentration of radionuclide *i* in air was obtained from the deposition density and the effective deposition velocity of radionuclide onto the ground surface:

$$TIA_i^{air} = \sigma_i / v, \quad (2)$$

where σ_i is the deposition density of radionuclide *i* at TOA (Bq m^{-2}); v=1.76×10^{-2} or 6.2×10^{-2} m s^{-1} is the effective deposition velocity of radionuclides onto the ground surface in case of dry deposition or of light rain (R<1 mm d^{-1}) (UNSCEAR, 1993) or wet deposition (Drozdovitch et al. 2008), respectively. The assumption was made that the radionuclide distribution in the deposited activity was not influenced by the type of deposition, i.e. wet *vs* dry.

Thyroid dose due to ingestion of radioiodine isotopes and ^{132}Te

The thyroid dose to a study subject of age *k* arising from ingestion of radioiodine isotopes (^{131}I, ^{132}I, ^{133}I, ^{135}I) and ^{132}Te with fresh cow's milk (in Tahiti), leafy vegetables, and drinking water, D_k^{ing} (mGy), was calculated as:

$$D_k^{ing} = \sum_i DC_{i,k}^{ing} \cdot \sum_m V_{m,k} \cdot PF_{i,m} \cdot TIA_{i,m}^{food}, \quad (3)$$

where $DC_{i,k}^{ing}$ is the age-dependent ingestion dose coefficient for the thyroid, i.e. the age-dependent internal thyroid dose due to intake via ingestion of unit activity of radionuclide *i* by a study subject of age *k* (mGy Bq^{-1}) (ICRP 1993, 1996a); $V_{m,k}$ is the consumption rate of foodstuff *m* and drinking water by the subject of age *k* (kg (L) d^{-1}); $PF_{i,m}$ is the processing factor, i.e., the fraction of radionuclide *i* remaining in foodstuff *m* after washing, culinary preparation and time delay between production and consumption (unitless);

$TIA_{i,m}^{food}$ is the time-integrated concentration of radionuclide i in foodstuff or drinking water m (Bq d kg^{-1} (L^{-1})).

Estimation of consumption rates at age k from the consumption rates reported for age 15—As mentioned above, daily consumption rates of foodstuffs for age 15 were reported by the study subjects during their personal interviews. To estimate the consumption rates at age k during childhood, the following equation was used:

$$V_{m,k} = V_{m,15} \cdot SF_{m,k}, \tag{4}$$

where $V_{m,k}$ is the consumption rate of foodstuff m by a study subject at age k (kg (L) d^{-1}); $V_{m,15}$ is the consumption rate of foodstuff m at age 15 that was reported by the study subject during her or his personal interview (kg (L) d^{-1}); $SF_{m,k}$ is the scaling factor to adjust the consumption rate of foodstuff m at age 15 to that at age k (unitless).

Archipelago-specific values of the scaling factor, $SF_{m,k}$, were derived from a focus-group survey of dietary patterns in French Polynesia that was performed within the framework of the Phase II study (Drozdovitch et al. 2019a). During this survey conducted in 2016–2017, data were collected on the frequency and amounts of fresh cow's milk, leafy vegetables, fâfâ, coco milk, coco copra, uru, banana, mango, papaya, manioc, taro, sweet potatoes, poultry, beef, pork, and goat meat (for Marquesas Islands), benitier (giant clam) and fish consumed by children for age groups ranging from birth to adulthood: 0−12 mo, 1−3.9 y, 4−6.9 y, 7−14.9 y, and 15−21 y. Table 4 provides, as example for Tahiti and Tuamotu archipelago, the age-dependent scaling factors for consumption of foodstuffs that were derived from the survey of Drozdovitch et al. (2019a).

It should be noted that the ICRP age groups are 0−12 mo, 1−2.9 y, 3−7.9 y, 8−12.9 y, 13−17.9 y, and adults, but that the consumption data were collected for age groups 0−12 mo, 1−3.9 y, 4−6.9 y, 7−14.9 y, and 15−21 y. Therefore, the values of the ingestion dose coefficient for the thyroid, $DC_{i,k}^{ing}$, and of the scaling factor to adjust the consumption rate, $SF_{m,k}$, were calculated for each year of age by linear interpolation of $DC_{i,k}^{ing}$ and $SF_{m,k}$ between center of age ranges, i.e., for ages < 1y, 1y, 5 y, 10 y, 15 y and 18 y (adults) and for ages <1 y, 2 y, 5 y, 11 y, and 18 y (adults) for $DC_{i,k}^{ing}$ and $SF_{m,k}$, respectively. The same procedure of interpolation was applied for the inhalation dose coefficient for the thyroid, $DC_{i,k}^{inh}$, the breathing rate, V_k^{air}, (eqn. (1)), the dose coefficient to fetus due to intake of radioiodine or tellurium isotopes by the mother of the subject via inhalation, $DC_{fetus}^{inh,i}(t_g)$, (eqn. (13)) and ingestion, $DC_{fetus}^{ing,i}(t_g)$, (eqn, (14)). The values of the dose coefficient to fetus were calculated for each week of gestation age by linear interpolation between values for gestation ages 5, 10, 15, 25, and 35 wks given by ICRP (2001).

Estimation of the time-integrated concentration in local cow's milk in Tahiti—The time-integrated concentration of radionuclide i in fresh cow's milk locally produced in

Tahiti was obtained as the integral over time from TOA to infinity of the concentration at time t (Müller and Pröhl, 1993; NCI, 1997):

$$A_{i,\,milk}(t) = \sigma_i \cdot F_i^* \cdot I_g \cdot TF_i \cdot \frac{\lambda_i^m}{\lambda_i^m - \lambda_i^w} \cdot \left(e^{-(\lambda_i^w + \lambda_i^r) \cdot t} - e^{-(\lambda_i^m + \lambda_i^r) \cdot t}\right), \qquad (5)$$

where $A_{i,milk}(t)$ is the concentration of radionuclide i in milk at time t (Bq L^{-1}); F_i^* is the mass-interception coefficient of radionuclide i by grass, i.e. the fraction of radionuclide initially retained by unit mass of grass or of leafy vegetable: 0.7 m^2 kg^{-1} (fresh weight) for iodine and tellurium for dry deposition, and 0.1 m^2 kg^{-1} for iodine and 0.2 m^2 kg^{-1} for tellurium for wet deposition (Gavrilin et al. 2004); I_g=10 kg d^{-1} is the daily intake of grass by cows, dry mass; TF_i is the cow's intake-to-milk transfer coefficient of radionuclide i (d L^{-1}). It was taken to be 3×10^{-3} and 5×10^{-4} d L^{-1} for stable iodine and tellurium, respectively (Müller and Pröhl, 1993); λ_i^m is biological transfer rate in cow's milk: 0.99 and 0.69 d^{-1} for stable iodine and tellurium, respectively (Müller and Pröhl, 1993); λ_i^w is the elimination rate of radionuclide i from grass due to processes of weathering and growth dilution: 0.069 and 0.047 d^{-1} for stable iodine and tellurium, respectively (Miller and Hoffman, 1983; Müller and Pröhl, 1993); λ_i^r is the radioactive decay constant of radionuclide i (d^{-1}).

When calculating the thyroid dose arising from ingestion of radionuclides with fresh cow's milk using eqn (3), the values of the processing factors, $PF_{i,milk}$, for radioiodine isotopes and ^{132}Te were equal to 1.0.

Estimation of the time-integrated concentration in leafy vegetables—Leafy vegetables consumed in French Polynesia include fâfâ, pota, watercress and spinach. The time-integrated concentration of radionuclide i in leafy vegetables was obtained as the integral over time from TOA to infinity of the concentration at time t, $A_{i,LV}(t)$:

$$A_{i,\,LV}(t) = \sigma_i \cdot F_i^* \cdot e^{-(\lambda_i^w + \lambda_i^r) \cdot t}. \qquad (6)$$

To calculate the thyroid dose arising from ingestion of radionuclides with leafy vegetables using eqn. (3), the values of the processing factors, $PF_{i,LV}$, for radioiodine isotopes were equal to 0.5 for watercress (washing) and 0.7 for fâfâ, pota and spinach (washing and boiling) (IAEA, 1997). For ^{132}Te, the values of the processing factors were equal to 1.0 for watercress (washing) and 0.9 for fâfâ, pota and spinach (washing and boiling).

Estimation of the time-integrated concentration in drinking water—Rainwater collected in a cistern was the only source of drinking water for all study subjects who resided in Tuamotu Archipelago and for some of the subjects who resided in other archipelagos. Typically, there was a family cistern that belonged to a single household and a communal cistern that could be used by the entire village. The variation with time of the concentration of radionuclide i in drinking water in a cistern was calculated as:

$$A_{i,water}(t) = \frac{1}{W(t)}[A_{i,water}(t-1) \cdot (W(t-1) \cdot e^{-\lambda_i^r \cdot \Delta t} - W_{cons}) + \sigma_i(t) \cdot S_{coll} \cdot SL], \tag{7}$$

where $A_{i,water}(t)$ is the water concentration of radionuclide i in the cistern at time t (Bq L^{-1}); $W(t)$ is the amount of water in the cistern at time t (L); $A_{i,water}(t-1)$ is the water concentration of radionuclide i in the cistern at time t-1 day (Bq L^{-1}); $W(t-1)$ is the amount of water in the cistern at time t-1 day (L); Δt=1 d is the calculation step; W_{cons} is the amount of cistern water consumed daily (L); S_{coll} is the area of rainwater collection for the cistern (m^2); SL is the solubility of radioisotopes in rainwater (unitless). The solubility of radioiodine isotopes and ^{132}Te in rainwater was taken to be 0.2 (Lessard et al. 1973) for direct fallout with TOA of H+24h or less. For TOA greater than one day, the solubility of radioiodine isotopes was equal to 1.

The amount of rainwater in a cistern was calculated as:

$$W(t) = \begin{Bmatrix} 0, \; if \; W(t) \le 0 \\ W(t-1) - V_{cons} + R(t) \cdot S_{coll}, \; if \; 0 < W(t) < W_{cistern} \\ W_{cistern}, \; if \; W(t) \ge W_{cistern} \end{Bmatrix} \tag{8}$$

where $R(t)$ is the precipitation at day t (MF, 2005) (mm); $W_{cistern}$ is the volume of the cistern equals to 15,000 and 90,000 L for family and communal cisterns, respectively (HCRFP, 1977).

The deposition density of radionuclide i, $\sigma_i(t)$, was defined as:

$$\sigma_i(t) = \begin{Bmatrix} \sigma_i, \; if \; t = TOA \; and \; R(t) \ne 0 \\ 0, \; if \; t \ne TOA \end{Bmatrix} \tag{9}$$

The daily consumption of water from the cistern was 200 and 2000 L for the family and the communal cisterns, and the area of rainwater collection for the cistern was 30 and 200 m^2, respectively (Drozdovitch et al. 2019a). The amount of water in the cisterns was calculated for each year of atmospheric testing for the time period starting 2 weeks before the first nuclear weapons test and ending 5 weeks after the last test of the year. The initial content of rainwater in the cistern was assumed to be 1/4 of its volume. The model considers that the daily consumption of drinking water varies from 0.25 L for 0–12 mo to 2.0 L for adults.

Thyroid dose due to external irradiation from radionuclides deposited on the ground

The thyroid dose for a study subject of age k due to external irradiation from radionuclides deposited on the ground, D_k^{ext} (mGy), was calculated as:

$$D_k^{ext} = BF_k \cdot \sum_i DC_{i,k}^{ext} \cdot \int_{t_1}^{t_2} \sigma_i(t) \tag{10}$$

where BF_k is the behavioral factor that takes into account the fraction of time spent indoors by the subject of age k and the shielding properties of residential building (unitless); $DC_{i,k}^{ext}$ is the thyroid dose rate coefficient for radionuclide i, that is, the absorbed dose rate in the thyroid (mGy d^{-1}) per unit deposition (Bq m^{-2}) of radionuclide i in a plane source covered by 3 mm of soil representing ground roughness (Bellamy et al. 2019); t_1 and t_2 are the times of beginning and end of residence at a given location (d).

Table 3 provides the list of radionuclides that were considered in the thyroid dose calculation due to external irradiation. The variation with time of the deposition density, $\sigma_i(t)$, of ^{95}Nb, ^{97}Nb, ^{132}I, and ^{140}La was estimated from the deposition density of their precursors, i.e., ^{95}Zr, ^{97}Zr, ^{132}Te, and ^{140}Ba, respectively. Radionuclides ^{91m}Y, ^{99m}Tc, ^{103m}Rh, ^{106}Rh, ^{137m}Ba and ^{144}Pr, with half-lives on the order of hours or less, were taken to be in radioactive equilibrium with their precursor, and the contributions from both nuclides were considered in a single conversion factor. It should be noted that the migration to deeper layers of soil, which occurs at time since deposition increases, was not considered, even for long-lived radionuclides, such as ^{137}Cs, ^{106}Ru, ^{144}Ce, as doses were calculated over the relatively short time from TOA until 31 December of the year when the test was conducted. This seems to be a reasonable simplification as, for example, dose due to external irradiation in 1969 from long-lived radionuclides deposited after the tests conducted in 1968 was, typically, around a few μGy.

The behavioral factor, BF_k, was calculated using the following equation:

$$BF_k = \frac{1}{24} \cdot \left[SF \cdot T_{indoors,k} + LF \cdot (24 - T_{indoors,k})\right], \quad (11)$$

where SF is the shielding factor, which is related to the attenuation of the gamma rays emitted outdoors by the building material of the dwellings (unitless). It was 0.1 for concrete, 0.3 for wood and 0.7 for straw and bamboo (Drozdovitch et al. 2008); $T_{indoors,k}$ is the time spent indoors in a day by a subject of age k, which depends for schoolchildren aged 7–14.9 y on the time of year: school days or school vacation (from 15 June to 15 August) (h). Age-, archipelago- and season-specific values of time spent indoors for the Polynesian population was collected by Drozdovitch et al. (2019a); LF is the location factor for outdoor conditions that depends on the type of environment (unitless). It was 0.5 for a typical urban environment and 0.7 for a rural environment (Drozdovitch et al. 2008).

Table 5 provides the values for BF_k, calculated using eqn (11), that were used in this study. If the study subject reported during the personal interview the type and construction material of residence, the value of the behavioral factor corresponding to the age k of the study subject and to her/his archipelago and type of residence was used in the dose calculation. If the study subject did not recall the type and construction material for her/his residence, the behavioral factor was estimated using the archipelago-specific distribution of types and construction materials of residences that were reported by the focus groups to be typical in the 1960s–1970s (Drozdovitch et al. 2019a).

Ingestion of long-lived ^{137}Cs with foodstuffs

The thyroid dose arising from ingestion of ^{137}Cs, D_k^{Cs} (mGy), was calculated as:

$$D_k^{Cs} = N \cdot D_k^{Cs} \cdot \sum_m V_{m,k} \cdot PF_m^{Cs} \cdot A_m^{Cs} \quad (12)$$

where N is the number of days of residence in a given archipelago during which the contaminated foodstuffs were consumed (d) in the year under consideration; D_k^{Cs} is the age-dependent thyroid dose coefficient for ^{137}Cs ingestion (ICRP, 1993) (mGy Bq^{-1}); $V_{m,k}$ is the consumption rate of foodstuff m by the subject of age k (see Table 2 for the list of foodstuffs) (kg (L) d^{-1}); PF_m^{Cs} is the processing factor that reflects the change in activity concentration of ^{137}Cs resulting from the culinary preparation of the raw product (unitless); A_m^{Cs} is the average annual concentration of ^{137}Cs in foodstuff m for each year from 1966 to 1974 (Bq kg^{-1}(L^{-1})).

Archipelago-specific average annual concentrations of ^{137}Cs in foodstuffs were derived from the results of measurements of ^{137}Cs in foodstuffs provided in reports to UNSCEAR (RF, 1967, 1969, 1971–1975) and in de-classified reports (SMSR 1970; SRCB 1975a,b, 1976a,b, 1978a,b). To calculate the thyroid dose arising from ingestion of ^{137}Cs using eqn. (12), the values of the processing factor were equal to 0.6 for root vegetables, 0.7 for fâfâ and pota, 0.8 for meat, 0.9 for leafy vegetables (except fâfâ and pota), fish, and uru (IAEA, 1997). For foodstuffs other than those listed above, the value of the processing factor was 1.0.

Study subjects exposed *in utero*

Fetal doses to the thyroid gland due to intakes of radioiodine isotopes (^{131}I, ^{132}I, ^{133}I, ^{135}I) and ^{132}Te by the mothers of the study subjects were calculated for inhalation of contaminated air and for ingestion of contaminated fresh cow's milk in Tahiti and of leafy vegetables and drinking water in all atolls and islands of interest.

The thyroid dose to a fetus arising from inhalation of contaminated air by the mother, D_{fetus}^{inh} (mGy), was calculated as:

$$D_{fetus}^{inh} = V_{adult}^{air} \cdot RF^{air} \cdot \sum_i TIA_i^{air} \cdot DC_{fetus}^{inh,i}(t_g), \quad (13)$$

where V_{adult}^{air} is the breathing rate of mother of the study subject (m^3 s^{-1}) (ICRP, 2002); $DC_{fetus}^{inh,i}(t_g)$ is the thyroid dose coefficient to a fetus of gestational age t_g, at time TOA of the test under consideration, per unit of acute inhalation intake of radioiodine or tellurium isotopes by the mother (ICRP 2001) (mGy Bq^{-1}).

The thyroid dose to a fetus arising from ingestion by the mother of radionuclide-contaminated foodstuffs and drinking water, D_{fetus}^{ing} (mGy), was calculated as:

$$D_{fetus}^{ing} = \sum_{g=n}^{l} \sum_{i} DC_{fetus}^{ing,i}(t_g) \cdot \sum_{m} V_{m,preg}^{*} \cdot PF_{i,m} \cdot TIA_{i,m}^{food}, \tag{14}$$

where $DC_{fetus}^{ing,i}(t_g)$ is the thyroid dose coefficient to fetus of gestation age t_g due to acute ingestion intake of radioiodine or tellurium isotopes by the mother of the subject (ICRP 2001) (mGy Bq^{-1}); n is the gestational age at time TOA of the test under consideration (wk); l is the gestational age two months after TOA of the test under consideration (wk); $V_{m,preg}^{*}$ is the consumption rate of foodstuff m or drinking water by the pregnant mother of the subject (kg (L) d^{-1}).

Archipelago-specific values of consumers' fractions and of consumption rates of locally-produced foodstuffs by pregnant women, which were obtained during the focus-group study (Drozdovitch et al. 2019a), are given in Table 6. The consumption rate of foodstuff m by pregnant women used in this study, $V_{m,preg}^{*}$, was calculated from the focus-group data as:

$$V_{m,preg}^{*} = P_{cons,preg} \cdot V_{m,preg}, \tag{15}$$

where $P_{cons,preg}$ is the fraction of consumers of foodstuff m among pregnant women (unitless); $V_{m,preg}$ is the consumption rate of foodstuff m by pregnant women who reported non-zero consumption of the foodstuff during the focus-group study (kg (L) d^{-1}).

Breastfed study subjects

Doses to the thyroid gland of breastfed children due to intakes of radioiodine isotopes (^{131}I, ^{132}I, ^{133}I, ^{135}I) and ^{132}Te by the mothers of the study subjects were calculated for inhalation of contaminated air and for ingestion of contaminated fresh cow's milk in Tahiti and of leafy vegetables and drinking water in all atolls and islands of interest.

The internal thyroid dose to a breastfed child arising from inhalation of contaminated air by the mother, D_{brfed}^{inh} (mGy), was calculated as:

$$D_{brfed}^{inh} = V_{adult}^{air} \cdot RF^{air} \cdot \sum_{i} TIA_{i}^{air} \cdot DC_{brfed}^{inh,i}, \tag{16}$$

where $DC_{brfed}^{inh,i}$ is the thyroid dose coefficient to a breastfed child due to inhalation of a specific radioiodine or tellurium isotope by the mother (ICRP 2004) (mGy Bq^{-1}).

The thyroid dose to a breastfed child arising from ingestion of radioiodine isotopes and ^{132}Te by mother with foodstuffs and drinking water, D_{brfed}^{ing} (mGy), was calculated as:

$$D_{brfed}^{ing} = \sum_{i} DC_{brfed}^{ing,i} \cdot \sum_{m} V_{m,lact}^{*} \cdot PF_{i,m} \cdot TIA_{i,m}^{food}, \tag{17}$$

where $DC_{brfed}^{ing,i}$ is the thyroid dose coefficient for the breastfed child due to ingestion of a specific radioiodine or tellurium isotopes by the mother (ICRP 2004) (mGy Bq^{-1}); $V_{m,lact}^{*}$ is the consumption rate of foodstuff m or drinking water by the lactating women (kg (L) d^{-1}).

Archipelago-specific values of consumers' fractions and consumption rates of foodstuffs by lactating women, which were obtained during the focus-group study (Drozdovitch et al. 2019a), are given in Table 7. By analogy with pregnant women, the consumption of foodstuff m by lactating women used in this study, $V_{m,lact}^{*}$, was calculated from the focus-group data as:

$$V_{m,lact}^{*} = P_{cons,lact} \cdot V_{m,lact}, \tag{18}$$

where $P_{cons,lact}$ is the fraction of consumers of foodstuff m among lactating women (unitless); $V_{m,lact}$ is the consumption rate of foodstuff m by lactating women who reported non-zero consumption of the foodstuff during the focus-group study (kg (L) d^{-1}).

Radiation data

The deposition densities of the radionuclides are the starting point for the estimation of the thyroid dose from most exposure pathways. Deposition densities were estimated directly from the measurements of total ground deposition or were derived from the measurements of total beta-activity in air and exposure rate associated with time of arrival of fallout at different locations in French Polynesia provided in the reports that were de-classified by the French Ministry of Defense and Veterans Affairs in 2013. Procedures of interpolation and extrapolation between islands where total beta-activity in air was measured were applied to estimate the deposition densities in islands where radiation measurements were not performed. A detailed description on how the deposition densities were estimated can be found elsewhere (Drozdovitch et al. 2019b).

Table 8 gives, as an example, the total deposition density and the deposition of ^{131}I estimated for the atmospheric nuclear weapons tests that contributed the most to radioactive contamination of selected islands and atolls in French Polynesia. The highest total depositions among inhabited islands and atolls of 6.1×10^7 Bq m^{-2} occurred in the Gambier Islands after test Aldébaran conducted on 2 July 1966. Significant deposition of 1.6×10^7 Bq m^{-2} and 1.2×10^7 Bq m^{-2} occurred also in Tureia after tests Arcturus on 2 July 1967 and Encelade on 12 June 1971, respectively (not shown). In Tahiti, the most populated island in French Polynesia, major fallout occurred after tests Centaure on 17 July 1974 (3.4×10^6 Bq m^{-2}), Sirius on 4 October 1966 (4.4×10^5 Bq m^{-2}) and Arcturus on 2 July 1967 (1.1×10^5 Bq m^{-2}). These three tests contributed around 94% to the total deposition density in Tahiti and around 85% of the ^{131}I deposition density (not shown). The highest deposition density in Marquesas Islands occurred in Hiva Oa after test Sirius (2.9×10^5 Bq m^{-2}) and in Austral Islands occurred in Raivavae after test Pallas on 18 August 1973 (3.8×10^5 Bq m^{-2}).

RESULTS

Individual thyroid dose estimates

The contributions of the different exposure pathways to the thyroid dose estimates are summarized in Table 9. The average thyroid dose due to all exposure pathways combined was estimated to be 4.7 mGy (range: 0.014 mGy to 36 mGy), with averages of 3.5 mGy (range: 0.002 mGy to 27 mGy) due to intake of ^{131}I, 0.75 mGy (range: 0.001 mGy to 14 mGy) due to intake of short-lived iodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te, 0.41 mGy (range: 0.005 mGy to 5.8 mGy) from external irradiation, and 0.08 mGy (range: ~0 mGy to 0.94 mGy) from ingestion of ^{137}Cs.

Fig. 3 shows the distribution of the total thyroid doses among the 804 study subjects. Around two-thirds of the subjects, 549 out of 804, received thyroid doses of less than 5 mGy. Twenty-five subjects (3.1% of the total) received thyroid doses greater than 15 mGy.

Table 10 presents the annual thyroid doses received by the study subjects during the period of atmospheric testing in French Polynesia (1966–1974). The lowest thyroid doses were received in 1968, 1970 and 1972. Atmospheric tests were not conducted in 1969, but exposure to fallout occurred due to ingestion of ^{137}Cs with locally produced food. The highest thyroid dose of 30 mGy is estimated to have been resulted from the test Aldébaran in 1966 by a study subject who resided in the Gambier Islands. In 1967, as fallout was deposited rather uniformly throughout French Polynesia, and highest thyroid doses of 6–7 mGy were received by study subjects who resided in Tahiti, Reao, and Takakoto (Tuamotu). In 1973, the maximal thyroid dose of 23 mGy was received after test Pallas by a study subject who resided in Rapa (Austral Islands). The major exposure in 1974 occurred after test Centaure in Tahiti and Society Islands with a maximal thyroid dose among the study subjects of 21 mGy.

Information on the thyroid doses received by the study subjects after each of the 41 atmospheric nuclear tests conducted in French Polynesia is presented in Table 11. There were six major tests that contributed the most to the thyroid exposure of French Polynesians. They are, in chronological order: Aldébaran, conducted on 2 July 1966, which resulted in a mean thyroid dose of 0.22 mGy among the study subjects, Sirius (4 October 1966, 0.27 mGy), Arcturus (2 July 1967, 0.84 mGy), Encelade (12 June 1971, 0.28 mGy), Pallas (18 August 1973, 0.30 mGy), and Centaure (17 July 1974, 2.4 mGy).

The means and ranges of the estimated thyroid doses received by the study subjects by island / atoll of residence during the atmospheric testing period from 1966 to 1974 are presented in Table 12. The mean thyroid doses were highest among the study subjects who resided in the Gambier Islands (17 mGy), Rapa (11 mGy), Maiao (9.5 mGy), Takakoto (7.4 mGy), Reao (5.7 mGy), Pukarua (5.4 mGy), Tubuai (5.1 mGy) and Tahiti (4.9 mGy). The mean thyroid doses normalized to the ^{131}I deposition density in each island/atoll of residence are also presented in Table 12. A large range of normalized thyroid doses, from 5.1×10^{-5} to 0.50 mGy, is observed.

DISCUSSION

This paper describes a large-scale dose reconstruction performed for the subjects of a case-control study of thyroid cancer among French Polynesians exposed to fallout from the atmospheric nuclear weapons tests conducted in 1966–1974. Overall, individual thyroid doses due to the main pathways of exposure were estimated for 564 and 240 subjects included in Phase I and Phase II of the study, respectively. We found that thyroid doses are higher among subjects included in Phase I of the study than among those included in Phase II: 5.0±4.1 mGy *vs* 4.0±4.6 mGy for the arithmetic mean ± SD and 3.9 mGy *vs* 2.5 mGy for the median, respectively (p<0.001).

We compared the individual thyroid doses calculated in this study, TD19, with the TD08 doses estimated previously by Drozdovitch et al. (2008) for the 564 subjects from Phase I of the study (Fig. 4). TD19 estimates were found to be higher than the TD08 estimates, 5.0 mGy *vs* 2.7 mGy for the arithmetic mean and 3.9 mGy *vs* 1.3 mGy for the median (p<0.001). The differences between the TD08 and TD19 estimates (Fig. 4) are mainly due to the following reasons:

- Dose estimates were found to be much lower in TD19 than in TD08 for the study subjects aged less than 4, for whom the consumption of leafy vegetables according to Drozdovitch et al. (2019a) was found to be zero (for age 0−12 mo) or very low (for age 1−3.9 y) (Table 4). In comparison, it was assumed in TD08 that the consumption rates of leafy vegetables at age 0−12 mo and 1−3.9 y were 20% and 65% of the consumption rate at age 15, respectively.
- Dose estimates were found to be much higher in TD19 in comparison with TD08 because of different reasons for different study subjects, such as the high consumption rates of leafy vegetables by the subjects who resided in the Austral Islands, the revision of the deposition density for test Pallas, the revision of the deposition densities in Tahiti from several tests, etc.

Intake of ^{131}I via inhalation and ingestion was estimated to be the main pathway of thyroid exposure accounting for 72% of the total dose. The mean contributions to the total thyroid dose from sources of exposure other than ^{131}I intake were found to be 14% for the intake of short-lived iodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te, 12% for external exposure, and around 2% for ^{137}Cs ingestion. With respect to external exposure, the main contributors to thyroid dose were ^{140}Ba+^{140}La, ^{132}Te+^{132}I, ^{95}Zr+^{95}Nb, ^{103}Ru, ^{131}I, and ^{239}Np and, in addition, ^{97}Zr+^{97}Nb, ^{133}I, ^{135}I, ^{99}Mo and ^{143}Ce, if the deposition density was due to direct fallout occurring within 24 hours after the test.

Fig. 5 compares the contributions of each exposure pathway to the total thyroid dose of the study subjects by archipelago: intake of ^{131}I and short-lived radioiodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te with (i) inhaled air, (ii) cow's milk, (iii) leafy vegetables, and (iv) drinking water, in addition to (v) external irradiation, and (vi) ingestion of ^{137}Cs with foodstuffs. The residents of the Society Islands received thyroid doses, mainly, from consumption of leafy vegetables and fresh cow's milk with minor contributions from other pathways. The large contribution to the thyroid dose from the consumption of leafy vegetables was found for the study subjects who resided in the Marquesas Islands and, especially, in the Austral Islands. For the Austral Islands, the relatively high consumption rates of leafy vegetables were reported both by the study subjects during their personal interview and during the focus-group study (Drozdovitch et al. 2019a). For the study subjects who resided in Tuamotu archipelago, drinking of rain water followed by consumption of leafy vegetables and external irradiation were found to be the major contributors to the thyroid dose.

It should be noted that Tureia, which is located 120 km to the north from nuclear test site Mururoa and where one of the largest deposition densities occurred, is not shown in the list of locations with highest thyroid doses among the study subjects (Table 12). It is because the only study subject from Tureia took residence in that island on 7 April 1973 and, therefore, was not exposed to the major fallout that occurred in Tureia after the tests conducted in 1966–1972. However, the radiation dose to the thyroid for a child born on 1 January 1966 who would have resided in Tureia during the entire testing campaign could have reached up to 500 mGy depending on individual behavior. One of the study subjects, who resided in the Gambier Islands and received an estimated thyroid dose of 0.01 mGy (Table 12), arrived in the island on 12 December 1973 and therefore was not exposed to the substantial fallout that occurred in Gambier after the tests conducted in 1966–1971. Other study subjects resided in the Gambier Islands in 1966–1974, and, consequently, their thyroid doses were much higher, with a mean of 17 mGy and a maximum of 36 mGy.

Improvement of the TD19 dosimetry model in comparison to TD08

As mentioned above, TD08 was substantially improved with new behavior and food consumption data for French Polynesians and revised deposition density values. Based on the focus-group discussions and the key-informant interviews, the following new data have been added and several assumptions used in TD08 were modified in TD19:

- To obtain the individual consumption rates of specific foodstuffs during childhood from the consumption rates at age 15, for which data were collected during the personal interviews of the study subjects, specific scaling factors for each archipelago in the 1960s–1970s were obtained from the focus-group study and used for the dose calculations (Table 4).
- Consumption rates of fâfâ and watercress salad, which were among the most important sources of ^{131}I intake with diet, were not considered in TD08 for the study subjects included in Phase I. In Phase II of the study, the consumption rates of fâfâ and watercress were collected during the focus-group study (Drozdovitch et al. 2019a); the mean age- and archipelago-specific values of the consumption rates were imputed to the study subjects of Phase I.
- The dietary data for pregnant and breastfeeding women, which were used in TD08, were based on limited data. TD19 used the archipelago-specific consumption rates of locally produced foodstuffs by women during pregnancy (Table 6) and lactation (Table 7) in the 1960s–1970s collected by the focus group study.

- Focus-group data (Drozdovitch et al. 2019a) indicate that there were significant differences in the time spent outdoors by school children between mid-June and mid-August (during school vacation) and other times during the year as well as between archipelagos; these differences had not been considered in TD08.
- In TD08, the assumption was made that home construction materials (affecting dose estimates due to external irradiation) were directly related to the type of residence, i.e. family houses were constructed from concrete only. This assumption was found not to be valid in the focus-group study. In fact, it was found that in all archipelagoes, except in the Austral Islands, wood (*pinex*) was widely used for family house construction (Drozdovitch et al. 2019a). Corrected values of archipelago-specific behavioral factor were used in TD19 (Table 5).
- TD08 did not consider that root vegetables (manioc, taro, sweet potatoes), mango and beef consumed in the Tuamotu archipelago (Table 4) and taro consumed in the Gambier Islands (not shown) were not locally produced.

Uncertainties in the thyroid dose estimates

There are several major sources of uncertainty in the estimates of the thyroid doses for the study subjects:

- The uncertainties attached to the estimation of deposition densities of specific radionuclides. When measurements of total beta-activity in air were available, the deposition density of the main contributors to the thyroid dose, such as ^{95}Zr +^{95}Nb, ^{103}Ru, ^{131}I, ^{132}Te+^{132}I, ^{133}I, ^{135}I, ^{140}Ba+^{140}La (radionuclides listed according to increasing mass number, not according to their importance) was generally estimated with an uncertainty factor of up to 2 (Drozdovitch et al. 2019b). For islands and atolls where measurements were not performed, procedures of interpolation and extrapolation resulted in uncertainties in the estimated deposition densities within a factor of 2 to 3 around the best estimate. In addition, the results obtained for atmospheric nuclear weapons tests conducted at the Nevada test site in the USA were used to estimate the deposition densities of specific radionuclides (Hicks 1981) because the corresponding data for the tests conducted in French Polynesia were not found in the open literature.
- The uncertainties attached to the values of the thyroid mass. It is challenging to estimate the degree of iodine deficiency and the values of the thyroid mass around the time of tests in the 1960s–1970s because data for that period of time are not available. The only data on thyroid mass-values in French Polynesians available to us were the results of thyroid volume measurements in a group of 83 individuals aged 12 to 17 conducted in 2007 (F. de Vathaire, personal communication, Paris, France, 2018). The mean thyroid mass-value in this group was found to be 9.2 g, which is consistent (within 30%) with the ICRP (2002) reference thyroid-mass value of 12 g for the same age group (15 years, according to the ICRP definition). We used in this study a thyroidal uptake of 30% and the age-dependent values of the thyroid mass recommended by ICRP (ICRP 2002).

- The uncertainties attached to the information obtained in 2001–2004 (for Phase I) and in 2014–2017 (for Phase II) during personal interviews regarding relocation history and individual diet. Recall of diet during childhood in distant past is strongly influenced by current diet (Dwyer et al. 1989) and is characterized by low reproducibility and validity if recollections exceeding 10 years (Maruti et al. 2005). For example, as information on the locations of the schools attended by the study subjects aged 7 to 14 was not available, it was assumed that the schools were located in the islands / atolls of residence.

The uncertainties in the doses, which were estimated in this study, were not evaluated in a quantitative manner. This important task, because of complexity of the model and multiple events of exposure that occurred in 1966–1974, will be a topic of a separate paper. However, based on the extensive assessment of uncertainties in thyroid doses performed for populations exposed to radioactive fallout from atmospheric nuclear weapons tests conducted at the Semipalatinsk Nuclear Test Site from 1949 to 1962 (Land et al. 2015), it was subjectively estimated that the overall uncertainties of the thyroid doses in this study are characterized, in average, by a geometric standard deviation of 2.5 to 3.0.

CONCLUSIONS

This paper presents the results of a large-scale dose reconstruction for 804 subjects of a case-control study of thyroid cancer among French Polynesians exposed to fallout from atmospheric nuclear weapons tests. Methodology of thyroid dose assessment was improved with new data obtained recently on detailed population lifestyle and detailed results of radiation monitoring in French Polynesia in 1966–1974. Individual thyroid doses due to intake of ^{131}I and of short-lived radioiodine isotopes (^{132}I, ^{133}I, ^{135}I) and ^{132}Te, external irradiation from gamma-emitted radionuclides deposited on the ground, and ingestion of long-lived ^{137}Cs were reconstructed. Thyroid doses were found to be low, the mean thyroid dose among the study subjects was found to be around 5 mGy while the highest dose was estimated to be around 36 mGy. Although the uncertainties in the doses, which were estimated in this study, were not evaluated in a quantitative manner, they were subjectively estimated to be relatively high and to be characterized, on average, by a geometric standard deviation around 2.5–3.0. Results of this study are being used to evaluate the risk of thyroid cancer among subjects of a case-control study of thyroid cancer in Polynesians exposed as children and adolescents to fallout from atmospheric nuclear weapons tests.

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APPENDIX. LIST OF PARAMETERS USED IN THE DOSIMETRY MODEL

Summary of parameters of the dosimetry model to calculate individual thyroid doses to the subjects of a case-control study is given in Table A1.

Table A1.

List of parameters used in the dosimetry model.

Parameter	Value	Symbol	Units	Eqn	Variable by
Breathing rate	(ICRP 2002)	V_k^{air}	m^3 s^{-1}	(1)	age of the subject
Reduction factor associated with indoor occupancy	1	RF^{air}	unitless	(1)	constant
Time-integrated concentration of radionuclide in air	DB[a]	TIA_i^{air}	Bq s m^{-3}	(1)	island/atoll, test
Inhalation dose coefficient for the thyroid	(ICRP 1995)	$DC_{i,k}^{inh}$	mGy Bq^{-1}	(1)	age of the subject, radionuclide
Time of arrival of fallout (TOA)	DB	H+t	h or d		island/atoll, test
Deposition density of radionuclide at TOA	calculated	σ_i	Bq m^{-2}	(2)	island/atoll, test
Effective deposition velocity of radionuclides onto the ground surface	1.76×10^{-2} (dry) 6.2×10^{-2} (wet)	ν	m s^{-1}	(2)	type of deposition
Ingestion dose coefficient for the thyroid	(ICRP 1993, 1996a)	$DC_{i,k}^{ing}$	mGy Bq^{-1}	(3)	age of the subject, radionuclide
Consumption rate of foodstuff and drinking water	calculated	$V_{m,k}$	kg (L) d^{-1}	(3)	age of the subject
Processing factor for foodstuff	DB	$PF_{i,m}$	unitless	(3)	radionuclide, food
Time-integrated concentration of radionuclide in foodstuff	calculated	$TIA_{i,m}^{food}$	Bq d kg^{-1} (L^{-1})	(3)	island/atoll, test
Consumption rate of foodstuff at age 15 y	questionnaire DB	$V_{m,15}$	kg (L) d^{-1}	(4)	individual
Scaling factor to adjust the consumption rate of foodstuff at age 15 y to that at age k	Table 4	$SF_{m,k}$	unitless	(4)	age of the subject, archipelago
Concentration of radionuclide in milk	calculated	$A_{i,milk}(t)$	Bq L^{-1}	(5)	test
Mass-interception coefficient of radionuclide by grass	DB	F_i^*	m^2 kg^{-1}	(5)	radionuclide, type of deposition
Daily intake of grass by cows (dry mass)	10	I_g	kg d^{-1}	(5)	constant
Cow's intake-to-milk transfer coefficient	3×10^{-3} (I) 5×10^{-4} (Te)	TF_i	d L^{-1}	(5)	element
Biological transfer rate in cow's milk	0.99 (I) 0.69 (Te)	λ_i^m	d^{-1}	(5)	element
Elimination rate of radionuclide from grass	0.069 (I) 0.047 (Te)	λ_i^w	d^{-1}	(5)	element
Radioactive decay constant	DB	λ_i^r	d^{-1}	(5)	radionuclide
Concentration of radionuclide in leafy vegetables	calculated	$A_{i,LV}(t)$	Bq kg^{-1}	(6)	test
Concentration of radionuclide in drinking water	calculated	$A_{i,water}(t)$	Bq L^{-1}	(7)	test
Amount of water in the cistern	calculated	$W(t)$	L	(7)	family/communal cistern, precipitation
Amount of cistern water consumed daily	200 (family) 2000 (communal)	W_{cons}	L	(7)	constant

Parameter	Value	Symbol	Units	Eqn	Variable by
Area of rainwater collection for the cistern	30 (family) 200 (communal)	S_{coll}	m^2	(7)	constant
Solubility of radioisotopes in rainwater	0.2 (TOA≤ H+24h) 1.0 (TOA> H+24h)	SL	unitless	(7)	constant
Precipitation at day *t*	DB	$R(t)$	mm	(8)	island/atoll
Volume of the cistern	15,000 (family) 90,000 (communal)	$W_{cistern}$	L	(8)	constant
Behavioral factor	Table 5 or calculated	BF_k	unitless	(10)	age of the subject, construction, time of year
Thyroid dose rate coefficient	(Bellamy et al. 2019)	$DC_{i,k}^{ext}$	mGy d^{-1} per Bq m^{-2}	(10)	age of the subject, radionuclide
Shielding factor	0.1 (concrete) 0.3 (wood) 0.7 (straw, bamboo)	SF	unitless	(11)	constant
Time spent indoors	DB	$T_{indoors,k}$	h	(11)	age of the subject, archipelago, time of year
Location factor for outdoor conditions	0.5 (urban) 0.7 (rural)	LF	unitless	(11)	constant
Number of days of residence in a given archipelago	questionnaire DB	N	d	(12)	individual
Thyroid dose coefficient for ^{137}Cs ingestion	(ICRP, 1993)	D_k^{Cs}	mGy Bq^{-1}	(12)	age of the subject, radionuclide
Average annual concentration of ^{137}Cs in foodstuff	DB	A_m^{Cs}	Bq kg^{-1}(L^{-1})	(12)	archipelago, year
Thyroid dose coefficient to a fetus due to acute inhalation intake of radionuclide by the mother	(ICRP 2001)	$DC_{fetus}^{inh,i}(t_g)$	mGy Bq^{-1}	(13)	gestational age, radionuclide
Thyroid dose coefficient to a fetus due to acute ingestion intake of radionuclide by the mother	(ICRP 2001)	$DC_{fetus}^{ing,i}(t_g)$	mGy Bq^{-1}	(14)	gestational age, radionuclide
Fraction of consumers of foodstuff among pregnant women	Table 6	$P_{cons,preg}$	unitless	(15)	archipelago
Consumption rate of foodstuff or drinking water by the pregnant women	Table 6	$V_{m,preg}$	kg (L) d^{-1}	(15)	archipelago
Thyroid dose coefficient to a breastfed child due to inhalation intake of radionuclide by the mother	(ICRP 2004)	$DC_{brfed}^{inh,i}$	mGy Bq^{-1}	(16)	radionuclide
Thyroid dose coefficient to a breastfed child due to ingestion intake of radionuclide by the mother	(ICRP 2004)	$DC_{brfed}^{ing,i}$	mGy Bq^{-1}	(17)	radionuclide
Fraction of consumers of foodstuff among lactating women	Table 7	$P_{cons,lact}$	unitless	(18)	archipelago
Consumption rate of foodstuff or drinking water by the lactating women	Table 7	$V_{m,lact}$	kg (L) d^{-1}	(18)	archipelago

[a]Database

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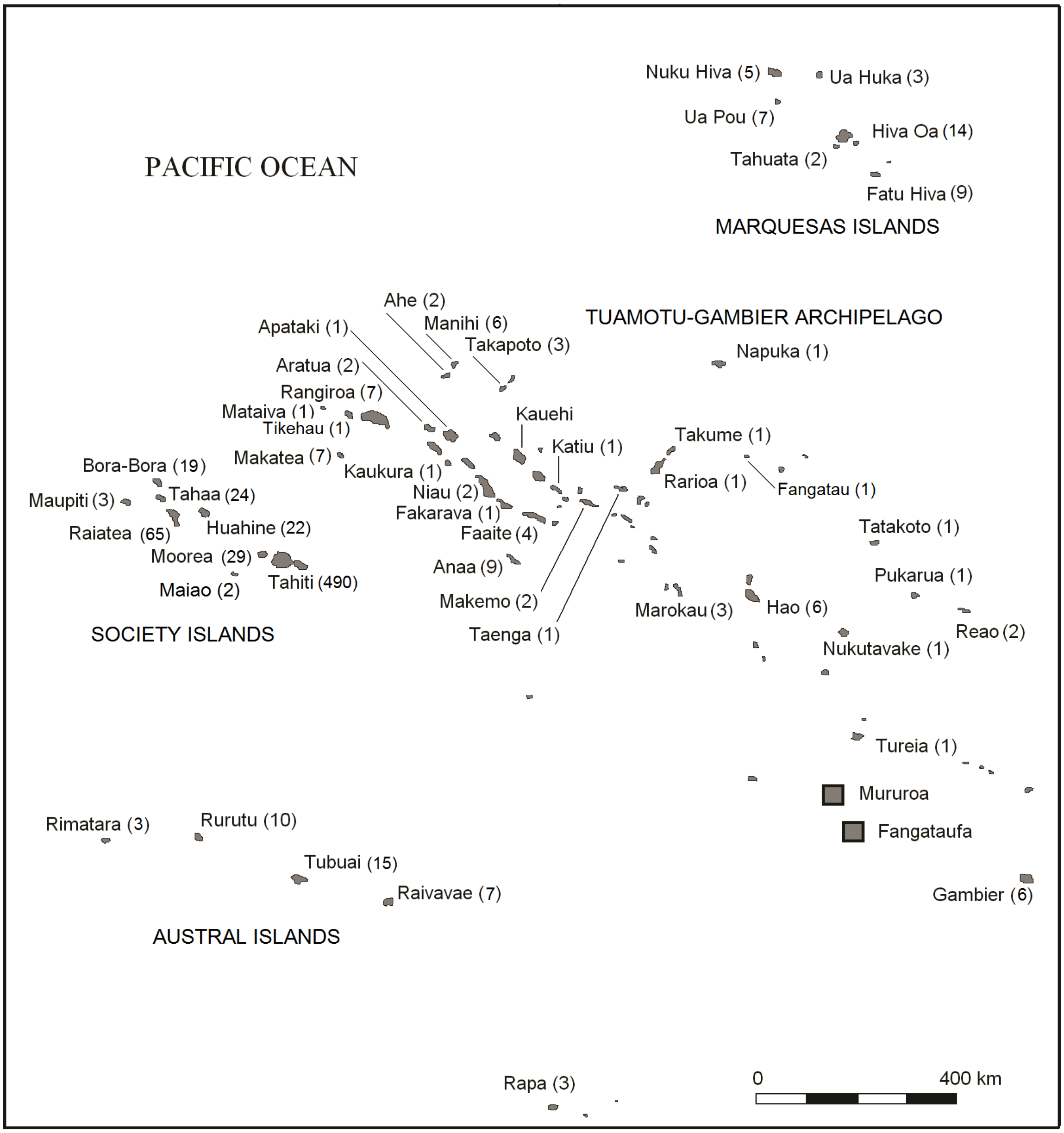

Fig. 1.

Map of French Polynesia. The numbers of study subjects who resided in each island or atoll in 1966–1974 are given within parentheses.

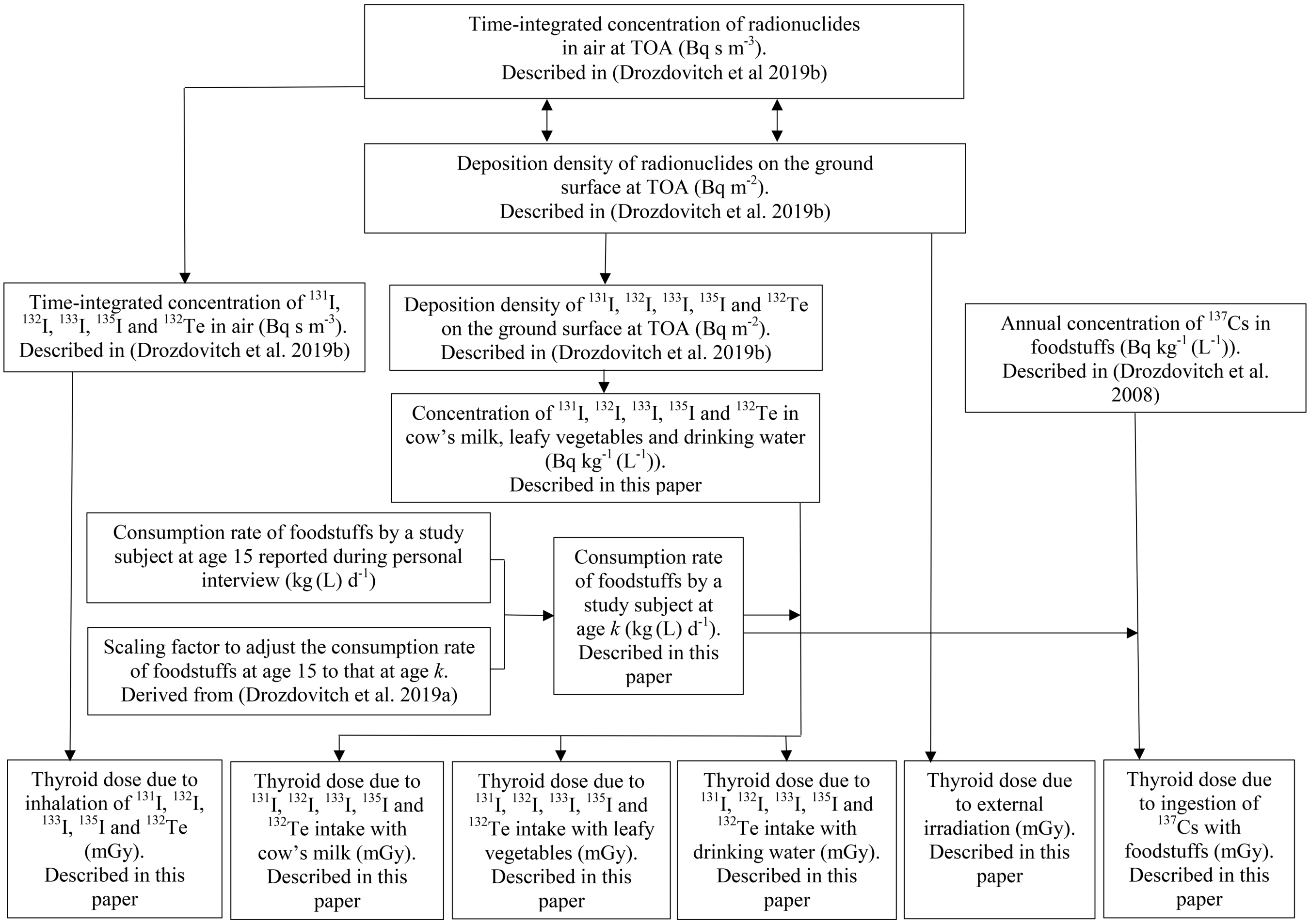

Fig. 2.

Scheme of the thyroid dose assessment for the subjects of a case-control study of thyroid cancer in French Polynesia.

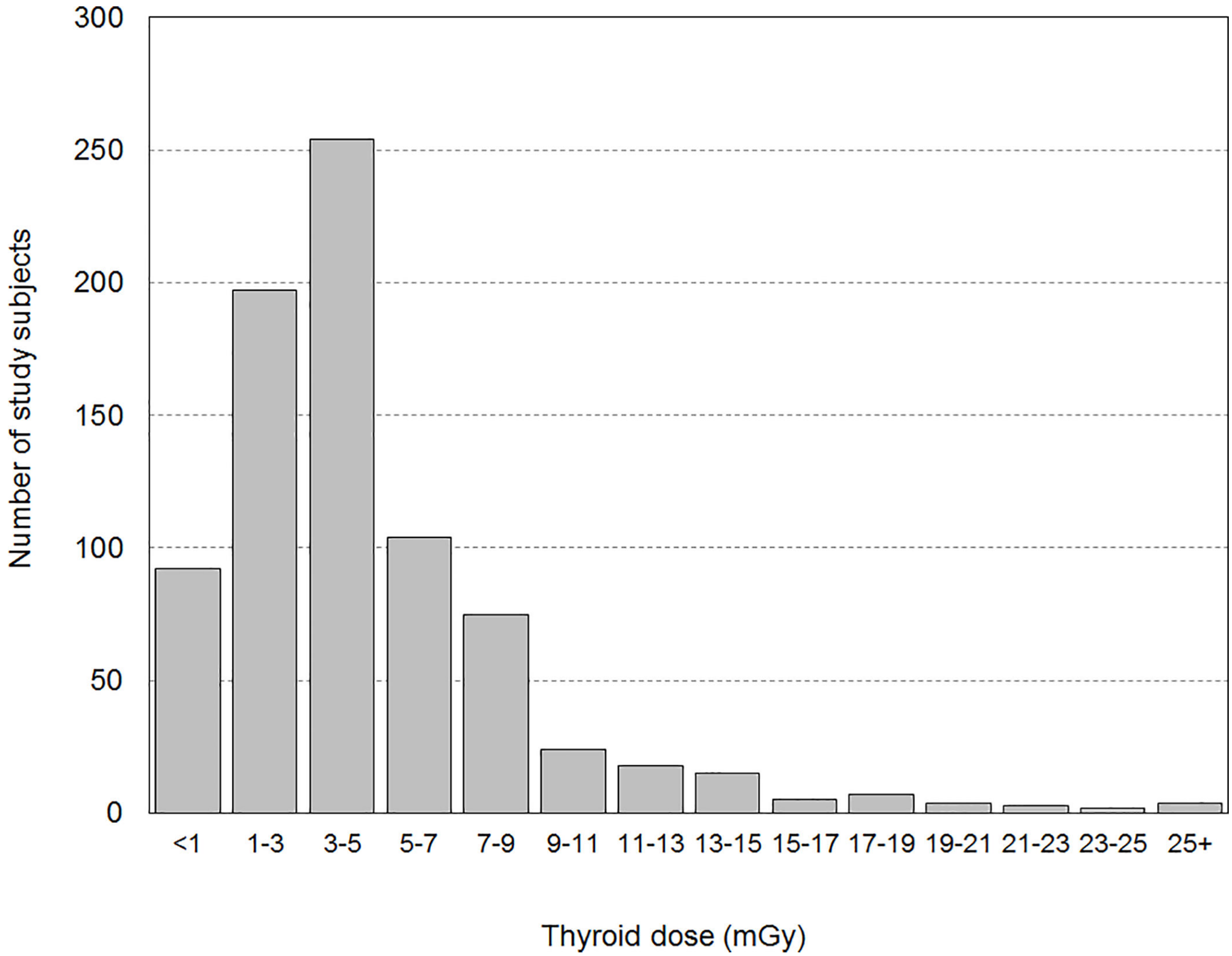

Fig. 3.
Distribution of the estimated thyroid doses among the study subjects.

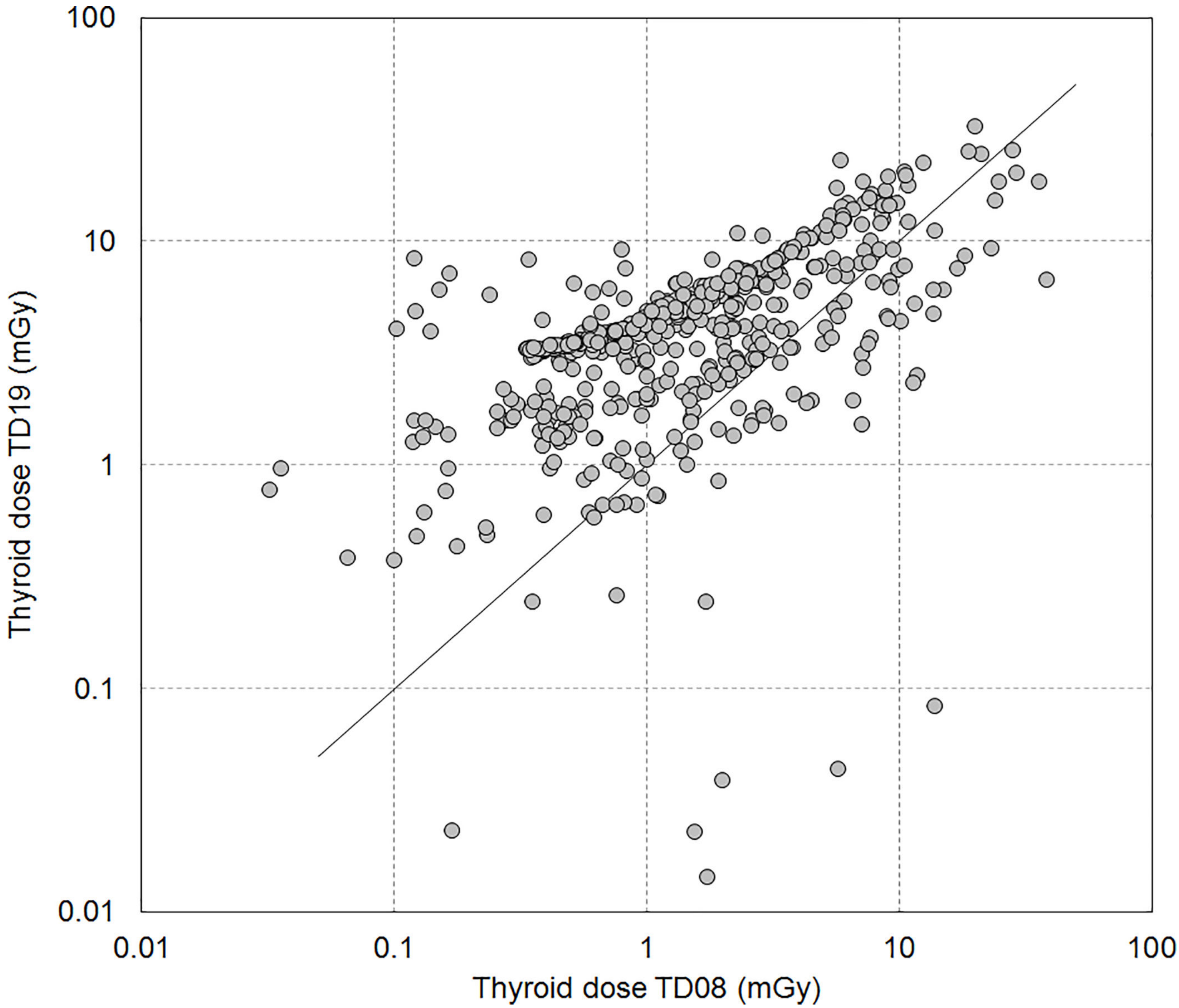

Fig. 4.

Comparison of individual thyroid doses estimated in TD08 and TD19 for the 564 exposed subjects included in Phase I of the study.

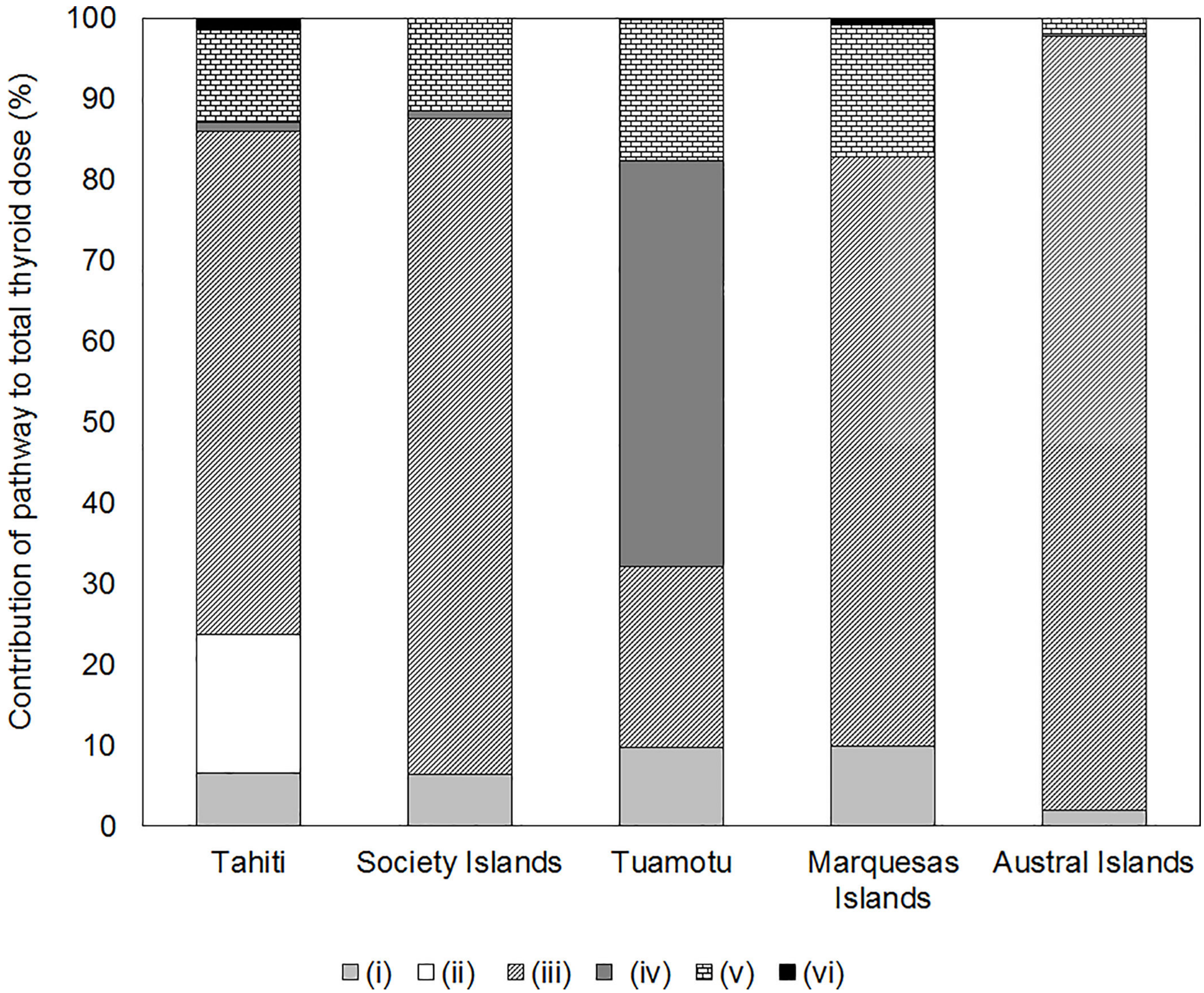

Fig. 5.

Contribution (%) of the exposure pathways to the total thyroid dose for the study subjects in each archipelago: intake of ^{131}I, ^{132}I, ^{133}I, ^{135}I and ^{132}Te with (i) inhaled air, (ii) cow's milk, (iii) leafy vegetables, and (iv) drinking water; also (v) external irradiation from the activity deposited on the ground, and (vi) ingestion of ^{137}Cs with foodstuffs.

Table 1.

Distribution of the study subjects according to year of birth.

Year of birth	Number of study subjects		Total
	Male	Female	
≤ 1942	18	48	66
1943	4	8	12
1944	−	22	22
1945	−	6	6
1946	−	18	18
1947	−	14	14
1948	1	10	11
1949	−	16	16
1950	2	24	26
1951	4	28	32
1952	4	13	17
1953	1	21	22
1954	8	21	29
1955	17	22	39
1956	7	38	45
1957	3	24	27
1958	8	43	51
1959	2	22	24
1960	7	26	33
1961	1	13	14
1962	−	29	29
1963	10	16	26
1964	1	37	38
1965	1	17	18
1966	−	23	23
1967	−	13	13
1968	2	16	18
1969	2	31	33
1970	3	18	21
1971	3	8	11
1972	−	19	19
1973	7	15	22
1974	−	9	9
Total	116	688	804

Table 2.

Fraction of consumers (P_{cons}), arithmetic mean (AM), standard deviation (SD), geometric mean (GM) and geometric standard deviation (GSD) of foodstuff consumption rates at age 15 reported by the study subjects during their personal interviews.

Foodstuff	P_{cons}	Consumption rates[a] (kg (L) d^{-1})			GSD
		AM	SD	GM	
Fresh cow's milk[b]	0.41	0.19	0.21	0.11	2.4
Leafy vegetables[c], including	0.67	0.059	0.075	0.033	2.7
Fâfâ[d]	0.60	0.028	0.040	0.017	2.9
Pota	0.48	0.0087	0.012	0.005	2.8
Watercress[d]	0.24	0.038	0.066	0.017	3.3
Coco milk	0.74	0.22	0.42	0.087	3.5
Coco copra	0.23	0.036	0.076	0.011	3.7
Uru (fruit of bread tree)	0.88	0.22	0.41	0.088	3.4
Banana	0.89	0.29	0.40	0.16	2.8
Mango	0.88	0.56	0.84	0.30	3.0
Papaya	0.84	0.18	0.23	0.094	2.7
Manioc	0.78	0.065	0.10	0.028	3.0
Taro	0.71	0.074	0.097	0.037	2.7
Sweet potatoes	0.82	0.074	0.084	0.043	2.5
Poultry	0.81	0.040	0.040	0.026	2.3
Beef	0.75	0.032	0.037	0.019	2.5
Pork	0.58	0.013	0.015	0.0086	2.5
Benitier	0.42	0.015	0.024	0.0072	3.1
Fish from sea	0.66	0.027	0.036	0.016	2.7
Fish from lagoon	0.89	0.068	0.067	0.041	2.3

[a]Consumption rates provided for consumers only.

[b]Residents of Tahiti only.

[c]Any leafy vegetables, including fâfâ, pota, watercress, spinach, lettuce.

[d]For Phase II of the study only.

Table 3.

Characteristics of the radionuclides that were considered in the assessment of thyroid doses in this study.

Radio-nuclide	Half-life[a]	Principal decay product (yield)	Mean photon energy[a] (MeV)	Mode of exposure to the thyroid gland
^{54}Mn	312.3 d		0.8348	External
^{89}Sr	50.5 d		0.909	External
^{90}Sr	28.9 y	^{90}Y (1.0)	–	External
^{90}Y	64.1 h		2.186	External
^{91}Sr	9.635 h	^{91m}Y (0.5825) ^{91}Y (0.4175)	0.734	External
^{91}Y	58.51 d		1.205	External
^{93}Y	10.19 h	^{93}Zr (1.0)	0.728	External
^{95}Zr	64.03 d	^{95}Nb (0.993)	0.7421	External
^{95}Nb	34.99 d		0.7656	External
^{97}Zr	16.744 h	^{97}Nb (1.0)	0.7109	External
^{97}Nb	72.17 m		0.665	External
^{99}Mo[b]	65.94 h		0.4992	External
^{103}Ru[b]	39.26 d		0.5014	External
^{106}Ru[b]	373.59 d		0.6022	External
^{125}Sb	2.759 y	^{125m}Te (0.2314)	0.4626	External
^{131}I	8.02 d		0.364	Internal, external
^{132}Te	3.204 d	^{132}I (1.0)	0.1992	Internal, external
^{132}I	2.30 h		0.7649	Internal, external
^{133}I	20.8 h		0.5845	Internal, external
^{135}I	6.572 h		0.619	Internal, external
^{136}Cs	13.16 d		0.7464	External
^{137}Cs[b]	30.17 y		0.6617	Internal, external
^{140}Ba	12.75 d	^{140}La (1.0)	0.3253	External
^{140}La	1.678 d		1.078	External
^{141}Ce	32.508 d		0.1454	External
^{143}Ce	33.039 d	^{143}Pr (1.0)	0.3383	External
^{143}Pr	13.572 d		0.7421	External
^{144}Ce[b]	284.91 d		0.1239	External
^{147}Nd	10.98 d	^{147}Pm (1.0)	0.2545	External
^{239}Np	2.357 d		0.1875	External

[a] ICRP (2008).

[b] Includes a contribution from the short-lived progeny ^{99m}Tc, ^{103m}Rh, ^{106}Rh, ^{137m}Ba and ^{144}Pr of ^{99}Mo, ^{103}Ru, ^{106}Ru, ^{137}Cs, and ^{144}Ce, respectively.

Table 4.

Scaling factors for age-dependent consumption rates of foodstuffs for Tahiti and Tuamotu archipelago (except Gambier Islands) derived from Drozdovitch et al. (2019a).

Foodstuff	Tahiti					Tuamotu archipelago (except Gambier Islands)				
	0–12 mo	1–3.9 y	4–6.9 y	7–14.9 y	15–21 y	0–12 mo	1–3.9 y	4–6.9 y	7–14.9 y	15–21 y
Fresh cow's milk	–[a]	0.34	0.39	1.03	1.00	–	–	–	–	–
Leafy vegetables[b]	–[a]	0.05	0.22	0.77	1.00	–[a]	–[a]	0.14	1.20	1.00
Fâfâ	–[a]	0.05	0.15	0.56	1.00	–[c]	–[c]	–[c]	–[c]	–[c]
Coco milk	0.02	0.22	0.53	0.50	1.00	0.27	0.33	0.57	0.86	1.00
Coco copra	0.03	0.13	0.82	0.80	1.00	–[a]	0.21	1.00	1.00	1.00
Uru	–[a]	0.03	0.32	0.59	1.00	–[a]	0.03	0.23	0.42	1.00
Banana	0.03	0.32	0.64	0.77	1.00	–[a]	0.06	0.52	0.97	1.00
Mango	0.06	0.38	0.52	0.79	1.00	–[c]	–[c]	–[c]	–[c]	–[c]
Papaya	0.25	0.38	0.42	0.43	1.00	–[a]	0.25	0.35	0.67	1.00
Manioc	–[a]	0.26	0.53	0.68	1.00	–[c]	–[c]	–[c]	–[c]	–[c]
Taro	–[a]	0.26	0.67	0.76	1.00	–[c]	–[c]	–[c]	–[c]	–[c]
Sweet potatoes	–[a]	0.31	0.70	0.81	1.00	–[c]	–[c]	–[c]	–[c]	–[c]
Poultry	–[a]	0.14	0.63	0.74	1.00	–[a]	0.08	0.39	1.13	1.00
Beef	–[a]	0.13	0.81	0.96	1.00	–[c]	–[c]	–[c]	–[c]	–[c]
Pork	–[a]	0.00	0.67	0.90	1.00	–[a]	–[a]	0.23	0.46	1.00
Benitier	–[a]	0.04	0.12	0.58	1.00	–[a]	–[a]	0.22	0.41	1.00
Fish[d]	0.01	0.19	0.39	0.73	1.00	–[a]	0.06	0.27	0.63	1.00

[a]Did not consume this foodstuff at this age.

[b]Including pota, watercress, spinach, lettuce.

[c]Did consume this foodstuff, but it was not locally produced.

[d] Either from sea or from lagoon.

Table 5.

Archipelago-specific values of the behavioral factor, BK_k, estimated in this study.

Age	Type of residence	Tahiti	Society Islands	Tuamotu archipelago	Gambier Islands	Marquesas Islands	Austral Islands
0–12 mo	Concrete house	0.30	0.31	0.35	0.30	0.30	0.31
	Wooden (*pinex*) house	0.50	0.51	0.55	0.50	0.50	0.51
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.10	0.12[a]	–	–	–	–
	Unknown[b]	0.50	0.59	0.63	0.47	0.52	0.31
1–3.9 y	Concrete house	0.33	0.32	0.34	0.33	0.36	0.34
	Wooden (*pinex*) house	0.53	0.52	0.54	0.53	0.56	0.54
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.16	0.14[a]	–	–	–	–
	Unknown	0.53	0.60	0.63	0.50	0.57	0.34
4–6.9 y	Concrete house	0.36	0.33	0.36	0.34	0.36	0.38
	Wooden (*pinex*) house	0.56	0.53	0.56	0.54	0.56	0.58
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.23	0.16[a]	–	–	–	–
	Unknown	0.55	0.61	0.64	0.51	0.53	0.38
7–14.9 y[c]	Concrete house	0.33	0.33	0.34	0.33	0.33	0.31
	Wooden (*pinex*) house	0.53	0.53	0.54	0.53	0.53	0.51
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.15	0.15[a]	–	–	–	–
	Unknown	0.52	0.60	0.63	0.50	0.50	0.31
7–14.9 y[d]	Concrete house	0.34	0.37	0.38	0.37	0.37	0.38
	Wooden (*pinex*) house	0.54	0.57	0.58	0.57	0.57	0.58
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.18	0.23[a]	–	–	–	–
	Unknown	0.54	0.63	0.65	0.54	0.53	0.38
15–21 y	Concrete house	0.33	0.35	0.38	0.37	0.33	0.38

Age	Type of residence	Tahiti	Society Islands	Tuamotu archipelago	Gambier Islands	Marquesas Islands	Austral Islands
	Wooden (*pinex*) house	0.53	0.55	0.58	0.57	0.53	0.58
	Bamboo house	0.70	0.70	0.70	0.70	0.70	0.70
	Concrete apartment	0.17	0.19[a]	–	–	–	–
	Unknown	0.53	0.62	0.65	0.54	0.50	0.54

[a]Only in Raiatea.

[b]For unknown type of residence behavior factor was estimated using archipelago-specific combination of type and construction material of residences according to Drozdovitch et al. (2019a).

[c]During school days.

[d]School vacation from 15 June to 15 August.

Table 6.

Archipelago-specific fractions of consumers ($P_{cons,preg}$) and consumption rates[a] of locally produced foodstuffs, $V_{m,preg}$, (kg (L) d^{-1}) by pregnant women (derived from (Drozdovitch et al. 2019a)).

Foodstuff	Tahiti		Society Islands		Tuamotu archipelago		Gambier Islands		Marquesas Islands		Austral Islands	
	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m
Fresh cow's milk	0.30	0.15	0.30	0.15	–	–	–	–	–	–	–	–
Leafy vegetables[b]	0.72	0.10	0.83	0.070	0.40	0.065	1.0	0.070	0.44	0.093	0.89	0.14
Fâfâ	0.66	0.074	0.50	0.060	–	–	0.43	0.14	–	–	0.89	0.20
Coco milk	0.74	0.29	0.67	0.19	1.0	0.36	1.0	0.31	0.56	0.11	0.78	0.16
Coco copra	0.85	0.077	0.75	0.060	0.93	0.10	0.71	0.056	1.0	0.31	0.78	0.11
Uru (fruit of bread tree)	0.77	0.20	0.83	0.090	0.93	0.47	1.0	0.21	1.0	0.090	0.78	0.18
Banana	0.89	0.23	0.67	0.16	0.93	0.18	1.0	0.44	0.89	0.45	1.0	0.36
Mango	0.91	0.41	0.75	0.56	–[c]	–[c]	1.0	0.33	0.89	0.61	0.67	0.58
Papaya	0.79	0.24	0.67	0.23	1.0	0.38	0.71	0.31	0.89	0.44	0.78	0.30
Manioc	0.60	0.10	0.83	0.074	–[c]	–[c]	1.0	0.13	0.78	0.10	0.89	0.20
Taro	0.91	0.13	0.83	0.078	–[c]	–[c]	–[c]	–[c]	0.56	0.036	1.0	0.35
Sweet potatoes	0.6	0.063	0.83	0.078	–[c]	–[c]	0.86	0.10	–[c]	–[c]	0.78	0.15
Poultry	0.74	0.070	0.75	0.064	0.87	0.068	1.0	0.15	0.78	0.19	0.78	0.074
Beef	0.51	0.036	0.58	0.031	–[c]	–[c]	0.57	0.044	0.78	0.055	0.33	0.041
Pork	0.38	0.049	0.42	0.050	0.87	0.052	0.71	0.069	0.78	0.16	0.56	0.045
Goat	–	–	–	–	–	–	–	–	0.78	0.065	–	–
Benitier	0.51	0.045	0.42	0.047	0.93	0.053	0.57	0.031	0.67	0.028	0.22	0.058
Fish (sea and lagoon)	0.98	0.23	0.83	0.27	1.0	0.50	1.0	0.24	0.67	0.22	1.0	0.29

[a]Consumption is provided for consumers only.

[b]Leafy vegetables including pota, watercress, spinach, lettuce.

[c]Did consume this food, but not locally produced.

Table 7.

Archipelago-specific fractions of consumers ($P_{cons,lact}$) and consumption rates[a] of locally produced foodstuffs, $V_{m,lact}$, (kg (L) d^{-1}) by lactating women (derived from (Drozdovitch et al. 2019a)).

Foodstuff	Tahiti		Society Islands		Tuamotu archipelago		Gambier Islands		Marquesas Islands		Austral Islands	
	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m	P_{cons}	V_m
Fresh cow's milk	0.30	0.17	0.30	0.15	–	–	–	–	–	–	–	–
Leafy vegetables[b]	0.70	0.10	0.75	0.068	0.40	0.065	1.0	0.070	0.44	0.093	0.89	0.14
Fâfâ	0.66	0.074	0.67	0.055	–	–	0.43	0.14	–	–	0.89	0.20
Coco milk	0.72	0.24	0.58	0.11	0.93	0.36	1.0	0.31	0.56	0.11	0.78	0.16
Coco copra	0.83	0.068	0.83	0.056	0.87	0.11	0.71	0.056	1.0	0.30	0.78	0.11
Uru (fruit of bread tree)	0.72	0.20	0.83	0.093	0.93	0.46	1.0	0.21	1.0	0.066	0.78	0.18
Banana	0.83	0.22	0.75	0.17	0.87	0.18	1.0	0.44	0.89	0.37	1.0	0.36
Mango	0.87	0.40	0.75	0.46	–[c]	–[c]	1.0	0.33	0.78	0.59	0.67	0.58
Papaya	0.77	0.23	0.75	0.28	1.0	0.38	0.71	0.31	0.89	0.38	0.78	0.30
Manioc	0.64	0.066	0.83	0.074	–[c]	–[c]	1.0	0.13	0.78	0.10	0.89	0.20
Taro	0.96	0.12	0.83	0.074	–[c]	–[c]	–[c]	–[c]	0.56	0.036	1.0	0.35
Sweet potatoes	0.62	0.061	0.83	0.074	–[c]	–[c]	0.86	0.10	–[c]	–[c]	0.78	0.15
Poultry	0.72	0.072	0.75	0.067	0.93	0.071	1.0	0.15	0.78	0.19	0.78	0.074
Beef	0.51	0.036	0.58	0.027	–[c]	–[c]	0.57	0.044	0.78	0.055	0.33	0.041
Pork	0.38	0.049	0.42	0.050	0.80	0.056	0.71	0.069	0.78	0.16	0.56	0.045
Goat	–	–	–	–	–	–	–	–	0.78	0.065	–	–
Benitier	0.49	0.039	0.42	0.051	0.87	0.054	0.57	0.031	0.67	0.028	0.22	0.058
Fish (sea and lagoon)	1.0	0.25	0.83	0.30	1.0	0.50	1.0	0.24	0.67	0.22	1.0	0.29

[a]Consumption is provided for consumers only.

[b]Leafy vegetables including pota, watercress, spinach, lettuce.

[c]Did consume this food, but not locally produced.

Table 8.

Total deposition density and ^{131}I deposition following atmospheric nuclear weapons tests estimated for selected islands and atolls in French Polynesia.

Name of test	Date of test (dd/mm/yyyy)	Archipelago	Island	TOA	Time-integrated beta-activity in air (Bq s m^{-3})	Precipitation (mm)	Deposition density [a] (Bq m^{-2})	
							Total	^{131}I
Aldébaran	02/07/1966	Tuamotu	Gambier [a]	H+10h45/H+13d	– [b] /2.5 × 10^5	13 / 111	6.1 × 10^7/1.6 × 10^4	5.4 × 10^5/1.5 × 10^3
Sirius	04/10/1966	Society	Tahiti [a]	H+18h / H+7d	6.4 × 10^6 /2.3 × 10^6	151 / 0	4.0 × 10^5 / 4.0 × 10^4	4.5 × 10^3 /2.7 × 10^3
		Tuamotu	Anaa [a]	H+12h / H+5d	1.1 × 10^7 / 2.2 × 10^6	19 / 5	6.5 × 10^5 / 1.4 × 10^5	6.0 × 10^3 /7.4 × 10^3
		Tuamotu	Nukutavake	H+5d	1.9 × 10^6	9	1.2 × 10^5	6.2 × 10^3
		Marquesas	Hiva Oa	H+6d	4.7 × 10^6	1	2.9 × 10^5	1.8 × 10^4
		Marquesas	Fatu Hiva	H+6d	4.7 × 10^6	0	8.2 × 10^4	5.0 × 10^3
Arcturus	02/07/1967	Society	Tahiti	H+4d	6.5 × 10^6	0	1.1 × 10^5	4.9 × 10^3
		Tuamotu	Hao	H+33h	– [c]	0	9.2 × 10^5	1.6 × 10^4
		Tuamotu	Katiu	H+3d	1.1 × 10^7	18	6.7 × 10^5	2.3 × 10^4
		Tuamotu	Reao	H+36h	– [c]	0	1.1 × 10^7	2.1 × 10^5
Encelade	12/06/1971	Society	Tahiti	H+10d	1.4 × 10^6	0	2.4 × 10^4	2.1 × 10^3
		Tuamotu	Hao	H+55h	– [b]	13	1.4 × 10^5	4.0 × 10^3
Pallas	18/08/1973	Austral	Raivavae	H+3d	2.2 × 10^7	0	3.8 × 10^5	1.3 × 10^4
		Austral	Rapa	H+5d	1.8 × 10^7	0	3.2 × 10^5	1.7 × 10^4
Centaure	17/07/1974	Society	Tahiti	H+56h	5.4 × 10^7	1	3.4 × 10^6	9.5 × 10^4
		Society	Moorea	H+58h	1.6 × 10^7	1	1.0 × 10^6	3.0 × 10^4
		Society	Bora-Bora	H+2.5d	1.4 × 10^7	32	8.8 × 10^5	2.6 × 10^4
		Tuamotu	Anaa	H+2d	6.6 × 10^7	18	4.1 × 10^6	1.0 × 10^5

[a] Direct fallout / secondary fallout.

[b] Measurements of exposure rate in air were used to reconstruct deposition density.

[c] Total deposition was measured.

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Table 9.

Estimated thyroid doses from all exposure pathways reconstructed for the study subjects.

Exposure pathway	Thyroid dose (mGy)		
	Min	Mean	Max
Intake of ^{131}I	0.002	3.5	27
Intake of short-lived ^{132}I, ^{133}I, ^{135}I, and ^{132}Te	0.001	0.75	14
External irradiation	0.005	0.41	5.8
^{137}Cs ingestion	3.4×10^{-5}	0.08	0.94
All exposure pathways	0.014	4.7	36

Table 10.

Thyroid doses received by the study subjects[a] in each year of the atmospheric testing period in French Polynesia (1966–1974).

Year	Thyroid dose (mGy)		
	Min	Mean	Max
1966	0.006	0.62	30
1967	0.018	1.0	7.2
1968	0.004	0.29	1.7
1969 [b]	1.1×10^{-4}	0.011	0.079
1970	0.007	0.15	1.0
1971	0.002	0.37	4.2
1972	2.6×10^{-4}	0.058	0.41
1973	0.001	0.33	23
1974	5.4×10^{-4}	2.5	21
All years	0.014	4.7	36

[a]Only individuals who resided at given year in French Polynesia and were exposed to fallout.

[b]Exposure due to ingestion of ^{137}Cs in locally-produced foodstuffs.

Table 11.

Estimated thyroid doses[a,b] received by the study subjects from each of the 41 atmospheric nuclear tests.

Test	Date of test (dd/mm/yyyy)	Thyroid dose (mGy)		
		Min	Mean	Max
Aldébaran	02/07/1966	0.002	0.22	30
Tamouré	19/07/1966	4.8×10^{-4}	0.018	0.19
Bételgeuse	11/09/1966	0.002	0.089	0.55
Rigel	24/09/1966	3.5×10^{-4}	0.012	0.29
Sirius	04/10/1966	0.006	0.27	3.1
Altaïr	05/06/1967	0.002	0.11	0.68
Antarès	27/06/1967	7.4×10^{-4}	0.035	0.24
Arcturus	02/07/1967	0.014	0.84	6.7
Capella	07/07/1968	1.8×10^{-4}	0.035	0.26
Castor	15/07/1968	0.001	0.051	0.29
Pollux	03/08/1968	0.004	0.15	0.92
Canopus	24/08/1968	9.8×10^{-4}	0.026	0.28
Procyon	08/09/1968	5.8×10^{-4}	0.025	0.17
Andromède	15/05/1970	1.8×10^{-4}	0.016	0.13
Cassiopée	22/05/1970	3.6×10^{-4}	0.011	0.081
Dragon	30/05/1970	6.5×10^{-5}	0.004	0.19
Eridan	24/06/1970	2.2×10^{-4}	0.008	0.16
Licorne	03/07/1970	0.001	0.030	0.35
Pégase	27/07/1970	3.7×10^{-4}	0.022	0.14
Orion	02/08/1970	0.001	0.027	0.18
Toucan	06/08/1970	7.4×10^{-4}	0.031	0.46
Dioné	05/06/1971	8.6×10^{-4}	0.012	0.34
Encelade	12/06/1971	0.003	0.28	2.3
Japet	04/07/1971	3.7×10^{-4}	0.040	0.47
Phoebé	08/08/1971	8.3×10^{-5}	0.023	3.6
Rhéa	14/08/1971	8.2×10^{-5}	0.014	0.32
Umbriel	25/06/1972	6.8×10^{-4}	0.021	0.19
Titania	30/06/1972	3.7×10^{-4}	0.014	0.24
Obéron	27/07/1972	1.4×10^{-4}	0.016	0.11
Euterpe	21/07/1973	2.7×10^{-4}	0.002	0.045
Melpomène	28/07/1973	4.9×10^{-4}	0.002	0.005
Pallas	18/08/1973	8.6×10^{-4}	0.30	23
Parthénope	24/08/1973	5.1×10^{-4}	0.029	0.37
Tamara	28/08/1973	0.001	0.011	0.12
Capricorne	16/06/1974	5.9×10^{-4}	0.009	0.064
Gémeaux	07/07/1974	1.0×10^{-4}	0.003	0.045

Test	Date of test (dd/mm/yyyy)	Thyroid dose (mGy)		
		Min	Mean	Max
Centaure	17/07/1974	4.1×10^{-4}	2.4	20
Maquis	25/07/1974	2.5×10^{-4}	0.015	0.11
Scorpion	15/08/1974	5.3×10^{-5}	0.060	0.51
Taureau	24/08/1974	2.7×10^{-4}	0.095	0.85
Verseau	14/10/1974	1.3×10^{-4}	0.012	0.13

[a]Only individuals who were exposed to fallout from given test.

[b]Do not include thyroid dose due to ^{137}Cs ingestion as ^{137}Cs activity in foodstuffs can not be separated between the tests.

Table 12.

Estimated thyroid doses[a] received by the study subjects by island / atoll of residence.

Archipelago	Island	Thyroid dose (mGy)			Mean thyroid dose normalized to ^{131}I deposition (mGy per kBq m^{-2})
		Min	Mean	Max	
Society	Tahiti	0.015	4.9	32	0.038
	Bora-Bora	0.17	1.3	8.1	0.030
	Huahine	0.006	2.0	9.1	0.047
	Maiao	6.2	9.5	13	0.079
	Maupiti	0.30	0.78	1.6	0.018
	Moorea	0.014	1.8	8.2	0.041
	Raiatea	0.004	1.6	7.6	0.039
	Tahaa	0.15	2.3	7.9	0.056
Tuamotu	Ahe	0.015	0.25	0.49	0.008
	Anaa	0.52	2.8	5.2	0.016
	Apataki	0.048	0.22	0.40	0.006
	Arutua	0.039	0.041	0.043	0.001
	Faaite	0.68	3.6	8.8	0.049
	Fakarava	0.020	1.1	2.1	0.016
	Fangatau	0.036	0.66	1.4	0.016
	Gambier	0.010	17	36	0.022
	Hao	0.007	0.88	2.4	0.023
	Katiu[b]	–	3.2	–	0.036
	Kauehi	0.023	0.95	1.9	0.012
	Kaukura[b]	–	0.93	–	0.024
	Makatea	0.37	1.5	3.7	0.027
	Makemo	0.68	1.8	3.9	0.019
	Manihi	0.097	0.60	1.3	0.018
	Marokau	0.003	0.72	1.5	0.021
	Mataiva[b]	–	0.31	–	0.017
	Napuka[b]	–	0.72	–	0.018
	Niau	0.27	1.4	3.3	0.021
	Nukutavake[b]	–	0.85	–	0.027
	Pukarua[b]	–	5.4	–	0.022
	Rangiroa	0.011	0.47	2.5	0.028
	Raroia[b]	–	0.40	–	0.010
	Reao	3.8	5.7	7.5	0.022
	Taenga[b]	–	0.091	–	9.5×10^{-4}
	Takapoto	0.36	0.58	0.73	0.018
	Takume[b]	–	0.082	–	0.002

Archipelago	Island	Thyroid dose (mGy)			Mean thyroid dose normalized to ^{131}I deposition (mGy per kBq m^{-2})
		Min	Mean	Max	
	Tatakoto[b]	–	7.4	–	0.030
	Tikehau[b]	–	1.3	–	0.072
	Tureia[b]	–	0.020	–	5.1×10^{-5}
Marquesas	Fatu Hiva	0.023	0.54	1.8	0.026
	Hiva Oa	0.061	1.1	7.0	0.031
	Nuku Hiva	0.019	0.61	3.8	0.047
	Tahuata	0.018	0.31	0.59	0.009
	Ua Huka	0.041	0.18	0.26	0.013
	Ua Pou	0.25	0.84	2.1	0.065
Austral	Raivavae	0.12	3.9	8.3	0.21
	Rapa	5.7	11	23	0.50
	Rimatara	0.34	1.9	7.1	0.10
	Rurutu	0.004	3.3	11	0.17
	Tubuai	0.067	5.1	18	0.27

[a]Only for individuals who were exposed during residence in given island / atoll.

[b]One study subject resided in given island / atoll.