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Fallout Radiation: Effects on Marshallese People

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12.1 Introduction

An accidental exposure of 290 human beings to radioactive fallout occurred in the Marshall Islands in 1954. The results of this accident brought into sharp focus effects of fallout radiation on man, some of which had not been anticipated. The medical findings have had an important influence on the field of medicine and military and civil defense planning. Since this experience affords the only example of fallout exposure of human beings, this chapter will be devoted to a review of the results of medical examinations of these people over a 13 year period since exposure. For a more detailed description of the findings the reader is referred to the list of references at the end of the chapter.

12.2 Fallout from Nuclear Detonations; The 1954 Fallout Accident

Radiation hazards from detonation of nuclear weapons can be divided into the immediate type and the residual or fallout type. With the detonation of a nuclear weapon there is an instantaneous release of tremendous numbers of gamma rays and neutrons which can produce penetrating radiation exposure to all personnel in the immediate vicinity. If the detonation has been at a high enough altitude, so that the fireball does not touch the ground, the fission product material will be ejected into the upper atmosphere where it will spread out over large areas of the world, gradually filtering down to earth in diluted and less active form. This is known as worldwide fallout. The

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bombs detonated over Hiroshima and Nagasaki, Japan were detonated high enough above the ground to result in the immediate type of radiation exposure of the people in these cities with little or no fallout occurring. The effect of this type of exposure to penetrating radiation is covered in Chapters 8, 9 and 10. However, when the fireball does touch the surface of the earth large amounts of incinerated earth, water and debris are sucked up into the bomb cloud and adhere to the radioactive fission and induced products. This mixture of particles settles to earth, in accordance with Stoke's law, for several hundred miles in a downwind direction. This is designated as the localized or "close-in" type of fallout and is characterized by radiation of much higher intensity than occurs with worldwide fallout. Such a fallout occurred in the Marshall Islands following the experimental detonation of a thermonuclear device at Bikini Island on March 1, 1954. Figure 1 shows a rough map of the fallout area.

The following table (Table 1) shows the island groups with degree of involvement.

Table 1

Summary of Fallout Exposure

Group*	Composition	Fallout observed	Estimated gamma dose(rads)	Extent of skin lesions
Rongelap	64 Marshallese	Heavy(snowlike)	175	Extensive
Ailingnae	18 Marshallese	Moderate(mistlike)	69	Less extensive
Rongerik	28 Americans	Moderate(mistlike)	78	Slight
Utirik	157 Marshallese	None	14	No skin lesions epilat:

*Also exposed were 23 Japanese fishermen who received a sublethal dose(Miyoshi and and Kumatori; Koyama; Kumatori et al.).

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The island groups were evacuated two days after the accident and received extensive medical examinations over a three months period. The American servicemen, who had been exposed at Rongerik Island, were then returned to their duty stations and the people of Utirik Atoll were returned to their home island. Because Rongelap was too highly contaminated, the people were moved to a temporary home (Majuro Atoll) until 1957, by which time radioactive levels on Rongelap had become acceptable for habitation, a new village was constructed for them and they were returned home (Fig. 2). The low levels of body burdens of radionuclides acquired by the people subsequent to their return to Rongelap will be discussed in Chapter 11.

12.3 Characteristics of Fallout Material

The chemical and physical makeup as well as the radiation characteristics of fallout will vary according to such conditions as the size of the weapon, height of burst and type of terrain or soil over which the detonation occurs. All fallout is particulate in nature, but the size, color and other characteristics of the particle will depend to some extent upon the chemical and physical properties of the soil. In the Marshall Island accident where the nuclear device was detonated near the ground, the fallout was a white powdery material largely composed of incinerated coral. The bulk of the radioactivity resided as insoluble oxides on particles of CaO of $Ca(OH)_2$. A large amount of activity was also carried on NaCl particles. Aside from the radioactive component, the calcium oxide in the material was in itself irritating to the skin due to its caustic nature. Fallout produced from other types of soil, not predominantly coral, might vary considerably in chemical and physical makeup, color and particle size.

12.4 Radioactive Hazards Associated with Fallout

Radioactive fallout may result in 3 types of exposure: (1) whole body exposure from gamma radiation; (2) radiation of the skin from deposition of fallout material thereon; and (3) the internal absorption of radioactive materials. Figure 3 is a rough diagramatic sketch showing the relatively uniform distribution of fallout on the ground, houses, trees and Marshallese personnel. The penetrating gamma radiation, which is represented by the wavy shaded areas, penetrates many yards in air before it is attenuated appreciably. There was, of course, no neutron radiation associated with the fallout. Beta radiation as represented by the stippling in the figure was completely attenuated in several feet of air. Estimates of the beta to gamma ratio vary widely up to 150/1 depending upon the exposure conditions. Alpha emitters were not present in the fallout to any great extent. Even if significant amounts had been, due to their weak penetrating ability, they would not likely add significantly to the skin damage, but might present a hazard from the point of view of internal absorption. Internal absorption of fallout occurs to some extent from inhalation but to a greater extent from ingestion of contaminated food and water.

12.5 Dose Estimations in the Marshallese

12.5.1 Whole body dose. The gamma radiation dose which resulted in a penetrating whole body exposure of the Marshallese was calculated from field instrument readings taken shortly after the accident, spectrometric and radiochemical data taken at the time of the fallout, estimates of duration of fallout, exposure time, etc. (Sondhaus et al.). Spectrographic data of the fallout showed gamma energy peaks at roughly 100, 700 and 1500 kev. The varied energy distributions, the greater depth dose due to the near 4π geometry of exposure make the fallout dosimetry significantly different from that of radiation therapy or experimental radiobiology. Table 1 shows the calculated gamma doses (dose in air) for the different island groups.

12.5.2 Skin Dose. Skin exposure was largely from beta radiation. The dose to the first few millimeters of the body surface were considerably greater than the midline gamma dose. Measurement of beta doses from the skin from fallout was an exceedingly difficult problem due to the complicated spectrum of different energy beta emitters present, the non-uniform distribution on the skin, and the fact that practical dose meters were not available to adequately discriminate between beta radiation and contaminating gamma radiation.

The penetration of beta particles into the skin depended on the beta energies of the component isotopes. Each isotope has its own characteristic spectrum of beta energies. Figure 4 shows roughly the tissue depth necessary to produce 50% attenuation of the beta particles from several isotopes. In animal studies the dose required to produce recognizable skin lesions by a particular beta emitter has been demonstrated to be dependent on the energy of the beta particles. (Henshaw et al., Davis and Alpen, Snider and Raper, Lushbaugh and Hale, Moritz and Henriques). For example it was found that it takes 20,000 to 30,000 rep ^{35}S(avg. energy 0.05 mev) to produce a reaction while it takes only 1,000 to 2,000 rep of ^{90}Sr or ^{90}Y(avg. energy 0.3-0.7 mev) to produce the same reaction.

In the Marshallese the dose to the skin could not be calculated with any degree of accuracy due to the aforementioned reasons. The majority of the beta radiation was of low energy(avg. 0.1 mev) and accounted for the fact that most of the lesions were superficial in nature. However there was sufficient penetration of more energetic components at the level of hair follicles to result in temporary epilation. Due to the rapid attenuation of beta particles in tissue, the skin surface dose may have been quite high. The contribution of beta radiation to the skin of the Marshallese from the ground has been estimated to have been about 2000 rep to the feet, 600 rep at hip level and 300 rep to the head. These doses were insufficient in themselves to produce detectable lesions though they probably contributed significantly to the severity of the foot lesions that occurred.

12.5.3 Internal Dose. The fallout material was about 10% soluble in water and completely soluble in acid. Ingestion appeared to be a more important route for internal absorption than did inhalation. The activity in the air settles out fairly rapidly, but contaminated food, water and utensils retain their activity for long periods of time (Cohn et al.).

The amount of fission products reaching the blood stream through the respiratory tract is a function of particle size, and the solubility of the airborne contaminants. The majority of particles with which the activity was associated was considerably larger than the optimum size for deposition in the alveolar tissue of the lung. Thus the probability of the retention of inhaled airborne contamination (except possibly for radioiodines) is not appreciable during the exposure period. This was borne out by the fact that animals sacrificed at early intervals from Rongelap showed the major portion of activity in their gastrointestinal tract. Based on these studies it was estimated that the amount of radioactive material in the gastrointestinal tract of the more heavily exposed Rongelap group at 1 day post detonation was approximately 3mCi.

The initial body burdens of internal emitters in the Rongelap people were estimated from data obtained by radiochemical analysis of the tissues of 2 pigs which had been simultaneously exposed, and subsequent comparison of human and animal urine analyses date (Cohn et al.). Information on the tissue distribution of fission products was obtained from the radiochemical analyses of the pigs living on Rongelap for 1 month. Of the internal activity 95% was localized in the skeleton of the pig. The pattern of deposition of the fission product mixture in the skeleton, as seen in an autoradiograph of a tibia of 1 of these pigs, resembles that seen after administration of alkaline earths, i.e. dense deposition in epiphyseal region (Figure 5).

In the first few months following the acute exposure, ^{89}Sr and ^{131}I (plus the shorter lived iodine isotopes) contributed the greatest internal radiation dose to the Marshallese. ^{89}Sr contributed the major portion of the beta dose to the skeleton at this time. The highest dose to an individual tissue (100 to 160 rep) was delivered to the thyroid by the iodine isotopes. Table 3 shows the estimates of the mean body burdens of the Marshallese at 1 and 82 days post exposure.

Table 2

Estimated Body Burden of Rongelap People (μc)

Isotope	Activity at Day 1	Activity at Day 82
Sr^{89}	1.6-2.2	0.19
Ba^{140}	0.34-2.7	0.021
Rare Earth Group	0-1.2	0.03
I^{131}(in thyroid gland)	6.4-11.2	0.0
Ru^{103}	0-0.013	-
Ca^{45}	0-0.019	0.0
Fissile Material	0-0.016 (μgm)	0.0

In view of the importance of the late development of thyroid abnormalities, the estimates of dose to the thyroid gland are presented in some detail here. The dose from radioactive iodine is determined by its uptake by the gland, its half-life in the gland, the size of the gland, and the relative proportion of the several radioisotopes of iodine involved. The relative distributions of the radioiodines in fallout is reasonably well known. In addition to ^{131}I, the isotopes ^{133}I, ^{135}I, and to a less extent ^{132}I contributed significantly to the thyroid dose. The only direct data available on the Rongelap people are radiochemical analyses of pooled urine samples taken 15 days and longer after the fallout. The 1 day thyroid content of ^{131}I was estimated to be 11.2 mCi (5.6 to 22.4 mCi). Assuming that 0.1% (0.05 to 0.2%) of the maximum thyroid burden(not corrected for physical decay) was excreted in the urine on the 15th day(Ng), James has calculated a dose of 160 rad to the adult thyroid from oral intake and inhalation of the various iodine isotopes, considering their fission yield, the average energy deposited in the thyroid gland per disintegration, and the time of absorption. The dose to the thyroid glands of children less than 4 years of age was then calculated by means of these factors with consideration of pulmonary function and the thyroid size of a child of that age. The small size of the childhood thyroid then resulted in a substantially larger dose. The total estimated mean dose from the various iodine isotopes to the childs gland was about 1000 rad, with a range of 700 to 1400 rads. The glands received an additional 175 rads from external gamma radiation. Although the skin overlying the thyroid gland was frequently the site of "beta burns" as shown in Figure 6, the deposit of radioactive materials in this area probably did not add significantly to the thyroid dose, since most of the beta irradiations were too weak to have penetrated to the depth of the gland.

The return of the Rongelapese to their home island in 1957 resulted in exposure to low levels of radionuclides in their environment. This is discussed in Chapter 11 .

12.6 Acute Effects

Examinations were carried out over a 72 day period initially followed by re-examinations at 6 months and then on an annual basis. Findings have been compared with Marshallese people who were not exposed. Since 1957 over 200 Rongelap people who were away from the island at the time of the accident have since returned to live with the exposed people. This group has formed an excellent comparison population.

12.6.1 Penetrating Gamma Radiation. During the first 48 hours typical radiation-induced gastrointestinal symptoms were associated with their gamma radiation exposure. About two-thirds of the Rongelap people experienced anorexia and nausea and a few vomited and had diarrhea. These symptoms were noted in the more heavily exposed group only. Following their evacuation from Rongelap the people appeared well until the development of skin lesions 2 weeks later. However, when first examined on the third day, it was apparent that significant radiation exposure had occurred in view of the lowered lymphocyte counts. Serial hematological determinations including total white count, differential, platelet count and hematocrit revealed that the hemopoietic depression was most marked in the 64 people on Rongelap who had received 175 rads, less marked in the other groups receiving less exposure. The average leukocyte and platelet counts are shown graphically in figures 7, 8 and 9. The first counts on the Rongelap group were done on post exposure day 3, at which time a drop in total white count was evident. The count then fluctuated perhaps as a result of the beta lesions, with no severe depression over the first 4 weeks. A marked depression then occurred, reaching minimum levels at 6 weeks. The counts approached the levels of the unexposed populations by 2 years. The time course of neutrophil count changes followed closely that of the total white count. Lymphocyte depression was early and profound with gradual return toward normal. The counts remained below that of the unexposed groups up until 11 years post exposure (See Fig. 19). The platelet count reached a low at approximately 4 weeks with fairly rapid initial recovery followed by secondary depression and slow return toward normal. The hematocrits at no time were remarkedly different from the unexposed levels.

At times of peak depression, some individuals had neutrophil counts below 1000 per mm^3 and platelet counts below 75,000 per mm^3. No infections attributable to the neutropenia were observed, however and an epidemic of upper respiratory infections at approximately the time of the maximum neutrophil depression was equally severe in the heavily and mildly exposed groups. No severe hemorrhagic phenomena could be attributed to the platelet depression except that menorrhagia occurred in 3 women. All individuals were ambulatory throughout, and no therapy (other than skin lesions) beyond that routinely required for any large group of individuals was necessary or administered because of the radiation exposure. Except for radiation-induced lesions of the skin, patchy epilation, and early gastrointestinal symptoms, no clear cut disease processes or symptoms were noted which could be related directly to radiation exposure. During the first few months post exposure about two-thirds of the exposed people exhibited loss of weight of several pounds. This may possibly have been related to their radiation exposure, although it was difficult to rule out effects due to change of environment.

12.6.2 Exposure of the Skin. During the first 24-48 hours after exposure about 25% of the Marshallese in the higher exposed groups experienced itching and burning sensations of the skin. A few complained of burning and lacrimation of the eyes. These symptoms were present to a lesser degree in the Americans on Rongerik who, being aware of the danger, took shelter in their aluminum buildings, bathed and changed clothes. These precautions greatly reduced the development of subsequent skin lesions in this group. The people on Utirik had no early skin symptoms. Skin lesions and epilation first appeared about 2 weeks after exposure. Erythema of the skin was not observed either during the early examinations when primary erythema might be expected or later when a secondary erythema might be expected. In the more heavily exposed Marshallese about 90% developed multiple, spotty, pigmented lesions on exposed parts of the body. Most of these burns were superficial in nature (See Fig.10). In the early stages all lesions were characterized by hyperpigmented macules, papules or raised plaques with a dry leathery texture. The pigmented stage of the superficial lesions was followed within several days by dry, scaly desquamation which proceeded from the central part of the lesion outward, leaving a pink to white thin epithelium which gradually repigmented. Only about 20% of the Marshallese group referred to developed ulcerating lesions and secondary infections occurred in a few cases. Burns on the dorsum of the feet were generally the most severe, showing bullae formation followed by ulceration(Fig. 11). At 13 years after exposure some of these lesions continue to show incomplete repigmentation of the skin with atrophy or scarring in some cases (see Fig. 12).

During the early stages of development of the lesions, itching, burning, and slight pain were experienced with the more superficial lesions. With deeper lesions pain was more severe. The deeper foot lesions were the most painful and caused some of the people to walk on their heels for several days during the acute stages. Some of the more severe lesions of the neck and axilla were painful when turning the head or raising the arms. The lesions did not produce any constitutional symptoms.

Spotty epilation of varied degrees occurred in 90% of the children and about 30% of the adults (see Fig. 13). Regrowth of hair commenced in all cases about 3 months post exposure and by 6 months hair was of normal color, texture and abundance (Fig. 14). Though change of color of hair from black to grey has been frequently observed in animals (Hance and Murphy; Chase), regrowth is usually of normal color in the human being. However, Conard and Tessmer have reported a case in which regrowth of the hair of the eyebrows(previously black) regrew white presumably due to exposure to fission products.

The histopathological changes induced in the skin by fallout in the Marshallese lesions were studied in sections of a number of biopsies. During the early, acute period of the lesions, the epidermis showed marked damage characterized by atrophy and flattening of the rete pegs with dis-organization of malpighian and basal layers and marked cellular changes (pleomorphic nuclei, pyknosis and cytoplasmic halos). Additional features were atrophy or absence of the stratum granulosum, imperfect keratinization, and loose fibrillation and hyperkeratosis of the stratum corneum. Cells laden with pigment were frequently present throughout the epidermis. In the dermis the changes were largely confined to the upper part with edema, telangiectasis of vessels with perivascular infiltration of lymphocytes. Chromatophores filled with melanin were prominent. Figure 15 shows some of these changes in a pigmented lesion biopsied 3 weeks after exposure.

By 6 months there was considerable improvement in the histological appearance of the lesions. The following changes were found to persist in varying degrees: focal atrophy of the stratum granulosum, slight focal pigmentary disturbances in cells of the basal layer, and slight disturbances in polarity of the epithelial cells in basal papillary projections. In the dermis, telangiectasis of slight to moderate degree persisted.*

The treatment of the lesions during the acute period was very similar to the treatment of thermal burns, mild lesions requiring only daily cleansing and application of bland antipruritic lotions and ointments. Calamine lotion with 1% phenol was soothing. With more severe lesions analgesic and anesthetic ointments were helpful in allaying more painful symptoms and in keeping the skin soft in lesions that were dry and thickened. Antibiotics applied locally and/or parenterally were used for secondary infections.

12.6.3 Exposure to Internally Absorbed Isotopes. There were no acute effects observed in the Marshallese that could be specifically attributed to the exposure to internally absorbed radionuclides. This is in contrast to serious late effects associated with the irradiation of the thyroid gland by radioiodines taken up during their period of acute exposure. This bears out the contention that iodine is the most hazardous element in fallout.

It might be argued that the gastrointestinal symptoms noted early in the Marshallese were to some extent caused by the radionuclides transient in the

*Histological studies were carried out by Dr. David A. Wood, San Francisco, California and Dr. Stuart Lippincott, Upton, New York.

gut. However, the external gamma ray exposure was sufficient to produce these symptoms alone, so it is difficult to assess the extent to which the internal exposure contributed to these acute effects.

The internal radiation hazard associated with fallout appears to be primarily due to long term chronic irradiation rather than to its acute effects.

12.7 Late Effects

12.7.1 General Health. Except for a few specific findings the exposed people of Rongelap have remained generally in good health during the 13 years since their exposure with no greater incidence of illnesses or degenerative diseases than seen in the unexposed comparison populations examined.

12.7.2 Mortality. Fifteen deaths have occurred amongst the 82 exposed Rongelap people giving a death rate somewhat greater than that of the unexposed populations. However there were a greater number of older people in the exposed group. There was no definite relation of the cause of death to radiation exposure.

12.7.3 Aging. Studies have been carried out to see if radiation produced any increased aging by measurement of such things as skin elasticity, hair greying, baldness, visual acuity, accommodation and arcus senilis of the eyes, audiometric measurements, blood pressure, strength, neuromuscular function, and body potassium levels (Conard,Eicher et al.). Most of these criteria showed good correlation with aging. By combining values for these parameters a biological age score for each individual was obtained (see Fig.16). However no significant difference in aging of the exposed as compared with the unexposed population was detected.

12.7.4 Fertility and Genetic Effects. Based on birth rates, fertility has been about equal in the exposed and unexposed populations. However about twice the number of miscarriages and stillbirths occurred in the exposed women during the first 4 years after exposure (41% or 13 of 32 pregnancies in the exposed and 16% or 8 of 49 pregnancies in the unexposed women). Fetal abnormalities do not appear to have been more numerous in the exposed group, though no specific genetic studies have been carried out. A low level of persisting chromosomal aberrations of the lymphocytes of the peripheral blood of the type induced by radiation have been noted at 10 years post exposure(Lisco and Conard),(see Fig. 17).

12.7.5 Cancer and Leukemia. No leukemia has been detected. The occurrence of 3 cases of cancer in the exposed group(2 of the female genital tract and 1 of the thyroid gland) represents a higher incidence in the exposed group, but due to the small numbers of people involved no correlation with radiation exposure can be made at this time.

12.7.6 Lens Opacities. Frequent slit-lamp observations have revealed no opacities of the lens characteristic of radiation exposure.*

12.7.7 Skin. Some degree of atrophy and scarring persisting in skin areas that had been more heavily irradiated have been noted (Fig. 11). Biopsies at these sites revealed that none of the lesions were neoplastic or showed alterations suggestive of a precancerous condition. In a few cases increasing numbers of pigmented maculae and moles have been noted in the areas of "beta

*Ophthalmological studies have been carried out by Colonel Austin Lowrey, MC USA, Ret burns" but these have appeared to be benign (see Fig. 18).

12.7.8 Bone Marrow.* A slight lag in complete recovery of peripheral blood elements in the exposed people compared to that of the unexposed population up until 11 years post exposure is believed to have represented a slight residual bone marrow injury (See Fig. 19).

12.7.9 Growth and Development Studies.** Height, weight, anthropometric measurements, and radiographic studies for bone age in children have revealed slight retardation in growth and development in the boys exposed on Rongelap who were less than 12 years of age at the time of exposure, particularly those 12 to 18 months of age at exposure. Only slight immaturity was noted in the female children of this group (Sutow, Conard and Griffith; Sutow and Conard). Figure 20 shows the relatively greater retardation in skeletal age in exposed boys than girls. Figure 21 shows the two boys with greatest growth retardation. The cause of growth retardation was not known until the recent detection of thyroid abnormalities.

12.7.10 Thyroid Findings. The most serious late effect of exposure has been related to the thyroid gland. Annual examinations had always included careful thyroid examinations including plasma protein bound iodine and cholesterol studies. Until recently these examinations had not revealed any apparent abnormality of the gland. In 1963 a thyroid nodule was first detected in a 12 year old exposed girl and in the following year two more teen age girls were discovered to have nodules. Since then the incidence of thyroid abnormalities has increased and at the present time (March 1967) 19 people with thyroid

*The later hematological studies have been under the direction of Dr. Leo Meyer, Long Island Jewish Hospital, Jamaica, New York.

**Growth and development studies have been carried out by Dr. W.W. Sutow, M. D. Anderson Hospital & Tumor Institute, Houston, Texas.

abnormalities have been noted, all of these occurring in the more heavily exposed group except one in an adult in the Ailingnae group (Conard, Rall and Sutow; Conard et al.,1967; Robbins, Rall and Conard). Only 3 such cases have been detected in adults, the remaining 16 cases having occurred in children exposed at less than 10 years of age. Table 3 shows the high incidence (84%) in this younger group and lack of such findings in the lesser and unexposed children. A low incidence was noted in the adults.

Table 3

Thyroid Nodules (Including Hypothyroidism)

In Marshallese Populations

(R=Rongelap; A=Ailingnae; UT=Utirik; C=Unexposed)

Group	Age At Exposure	No. in Group	Gamma Dose (rads)	Estimated Thyroid Dose (I*, rads)	% Thyroid Nodules
R	<10	19	175	700-1400	84.2
A	<10	6	69	275-550	0.0
UT	<10	40	14	55-110	0.0
C	<10	61	0	0	0.0
R	>10	36	175	160	5.5
A	>10	8	69	55	12.5
UT	>10	59	14	15	3.4
C	>10	133	0	0	2.3

*In estimating the thyroid doses to the Ailingnae and Utirik exposed group, it was assumed that such doses were proportional to the thyroid doses of the Rongelap exposed group, based on relative whole body gamma dose received.

Thyroid surgery was performed on 9 children and 2 adults.** All nodules were found to be benign in the children and one adult. The other adult, a 41 year old woman in the higher exposure group had a thyroid cancer. In addition to

**Surgery on the first 3 cases was performed by Captain C.A. Broadeus(MC)USN, U.S. Naval Hospital, Guam, and on the other 8 by Dr. Bentley P. Colcock, Lahey Clinic, Boston, Massachusetts.

those cases with thyroid nodules, 2 boys with greatestgrowth retardation developed atrophy of the thyroid gland with signs of hypothyroidism(Fig. 21).

Figure 22 shows the gross appearance of the nodules at surgery. Note the varied size of the nodules from several millimeters to several centimeters, some being cystic, and some hemorrhagic. Figure 23 shows the microscopic characteristics of these benign nodules. They resemble closely adenomatous goiter usually seen with iodine deficiency and definite radiation effects were not identified in the glands by most pathologists. Figure 24 shows the gross and Figure 25 the microscopic appearance of the mixed papillary and follicular cancer with localized metastases that occurred in the woman referred to above.

It has become increasingly clear that the growth retardation noted in the children is probably associated with thyroid deficiency, even though a hypothyroid tendency was not detected in earlier years when the growth retardation was first noted. It has since been discovered that a high level of iodoprotein is normally present in the Marshallese people which gives a falsely high PBI level (Rall and Conard). This may have masked a low degree of hormone deficiency. However by 11 years after exposure the 2 boys showing the greatest growth retardation developed characteristics of frank hypothyroidism with atrophy of the thyroid gland, drop in PBI level to less than 2 μg%, development of coarse facial features, dry skin and Achilles reflex with sluggish return and bone dysgenesis. High pituitary TSH levels indicated a primary hypothyroidism. Several other children with less degree of growth retardation have recently shown some degree of thyroid deficiency also.

In view of the seriousness of these findings it was decided to initiate thyroid hormone therapy on the exposed people. The rational for this form of therapy was that by furnishing normal levels of exogenous thyroid hormone, pituitary TSH levels would be repressed and remove the thyroid gland from stimulation of that hormone. It is thus hoped that further development of nodules and possible malignancy might be prevented and, of equal importance, enhancement of growth and development in the children might result. Conclusive results of this treatment must await further observations and a stricter treatment regimen. However it does appear that several nodules have reduced on this treatment and some children may be showing increased growth. Figure 26 shows the results of hormone treatment on the 2 boys who had shown growth retardation, referred to before and shown in Figure 21. It can be seen that there has been a tendency to an increase in skeletal development coincident with the institution of the thyroid therapy.

The exclusive development of these thyroid abnormalities in the irradiated Marshallese children seems clearly to indicate the radiation etiology. The development of such abnormalities is consistent with the known etiological relationship of irradiation of the thyroid gland and the development of such lesions(Doniach, Kneeland et al.; Lindsay et al.; Goldberg and Chaikoff; Potter et al.). The high incidence in the children is probably related to the larger dose of radiation received by their smaller glands. Though the pathological changes in the nodules are similar to those seen in iodine deficiency goiter there is no reason to suspect such causal relationship in the Marshallese cases since dietary iodine is normal, urinary excretion of iodine is in the normal range and there are no known goitrogenic foods.

The radiation induction of such changes in the thyroid could conceivably result from injury to the thyroid gland reducing the hormone output and thus calling on the pituitary to secrete a greater amount of TSH. This would give the thyroid picture of hypertrophy in those follicles capable of responding to such hormone and the presence also of atrophic follicles incapable of responding. The development of thyroid nodules following ^{131}I treatment of hyperthyroidism (Sheline et al.) and following x-ray treatment of infants for thymic enlargement (Pincus, Reichlin and Hempelmann) has been reported. The occurrence of radiation-induced mutations would enhance the possible development of malignancy in the irradiated glands. Such a possible development in the Marshallese subjects must be borne in mind. This is particularly true in the case of the children since many retrospective and prospective studies have shown a causal relationship of irradiation of the neck region in infants with the later development of thyroid cancer (Duffy and Fitzgerald; Simpson, Hempelmann and Fuller; Warren, Alvizouri and Colcock). An increased incidence of cancer of the thyroid has been reported in the Japanese exposed to the atomic bomb (Socolow). It is of course not possible to prove the causal relationship of irradiation in the case of cancer of the thyroid in the exposed Marshallese woman but in view of the low incidence of such malignancies in the Marshallese this possibility must be seriously considered.

The causal relationship of thyroid deficiency and growth retardation in the children in the more heavily exposed group seems reasonably well established and it is hoped that thyroid hormone treatment will enhance their growth and development.

12.8 Summary and Conclusions

The findings on the Marshallese population accidentally exposed to radioactive fallout 13 years ago allow accurate documentation of the effects of localized fallout radiation on human beings. Since this population did not protect themselves during the exposure to fallout, this represents an extreme case particularly in regard to the skin and from internally deposited radionuclides. The radiation exposure resulted in 3 general classes of injury: a. the syndrome of whole body radiation injury produced by penetrating gamma radiation, b. superficial radiation burns produced by soft radiation (beta and low energy X or gamma radiations), c. radiation injury produced by the deposition of radionuclides within the body resulting in late thyroid effects only so far. The most serious of the acute effects was related to the hematological depression from exposure to the gamma radiation. The time course of hematological changes differed in important aspects from that seen in most laboratory animals. The lymphocytes showed an early depression. The neutrophils did not reach a minimum until approximately 6 weeks. The platelet count fell in a regular fashion reaching a low at approximately 30 days. The rate of recovery of the blood elements in the Marshallese was slower than would be anticipated from animal data and was not considered complete until about 11 years after exposure. These findings are consistent with the incomplete data available on the Japanese exposed at Hiroshima and Nagasaki, with the findings in the Japanese fishermen exposed in the same accident, and with the findings on human beings exposed in reactor accidents. They are also consistent with findings in patients exposed therapeutically either to total body radiation or internally administered radionuclides.

As a result of this accident, the potentialities of serious injury to the skin from fallout became apparent(even though a sublethal dose of radiation was received). However, the skin effects are less serious than those produced by whole body gamma radiation. Burns from beta radiation are spotty and more superficial than those produced by more penetrating radiations. Consequently they are generally less painful and heal more rapidly with fewer complications. Early irritation of the eyes and skin from fallout and belated developments of symptomatology associated with the beta burns may not only be annoying but disabling, and may complicate the course of the acute radiation syndrome. From the Marshallese experience the importance of protective measures (taking shelter, covering of the skin by clothing, and prompt cleansing of the skin) were obvious. There is no special treatment for beta burns and the usual measures taken in the treatment of ordinary radiation or thermal burns proved satisfactory.

It is encouraging that radiochemical urine analyses showed rapid elimination of the internally absorbed radionuclides, with barely detectable levels by 6 months. The particle sizes of the fallout material were too large for optimal alveolar absorption from inhalation and the major absorption occurred in the G.I. Tract after the ingestion of contaminated food and water. Though no obvious acute effects were associated with internally absorbed radionuclides in the Marshallese, the late effects of radioiodine absorption proved to be far more serious than had been anticipated. The internal hazard could have been largely avoided by consuming food and water which had been protected from fallout contamination (canned goods, etc.). Certain chelating agents and chemical compounds such as EDTA and zirconium citrate have shown some ability to accelerate the removal of internal emitters, but it is doubtful that the use of such agents would be feasible in the acute period following a nuclear bomb attack. It seems clear that the chief radiological concern at early times following an explosion will be those of total body radiation from gamma rays and skin irradiation from beta emitters.

Except for the development of thyroid abnormalities and slight growth retardation in some exposed children, overt evidence of late effects of exposure have been minimal in the Marshallese. General health and disease incidence have remained about the same in the exposed and unexposed populations with no clear cut effects noted on mortality, birth rate, longevity, aging, incidence of malignancy and degenerative diseases or opacities of the lens. A few other positive findings appear to be associated with their exposure such as an increase in miscarriages and stillbirths in the exposed women during the first 4 years after exposure, a lag in complete return of peripheral blood counts to the unexposed levels during the decade after exposure and the persistence of a low level of chromosomal aberrations at 10 years post exposure. The most important late findings have had to do with growth and development in the exposed children and the development of thyroid abnormalities. Slight retardation of growth has been noted mainly in the boys exposed at less than 12 years of age first noted a few years after exposure. Since 9 years post exposure thyroid nodules have developed in 17 cases and thyroid deficiency in 2 cases(all but 3 of these were in children exposed at less than 10 years of age). These effects are believed to be related to injury of the thyroid gland from exposure to radioiodines and gamma radiation at the time of the fallout. The detection of thyroid damage was hindered by its slow onset and due to the fact that the true PBI levels were masked due to the finding of elevated levels of iodoprotein in the Marshallese people. Thyroid surgery revealed that all nodules were benign except for 1 exposed adult woman with a cancer of the gland. The development of marked thyroid deficiency in 2 boys who showed greatest growth retardation and to a lesser degree in several other children clearly indicates the correlation of thyroid deficiency with growth retardation in the exposed children and emphasizes the seriousness of such thyroid exposure in children. Though dose estimates for the thyroid glands are only approximate, the Marshallese experience helps to define the dose range in which thyroid damage may occur. Preliminary evaluation of the effects of thyroid hormone therapy in the Marshallese indicates that such therapy may be of value, both as a prophylatic measure to prevent development of thyroid abnormalities including malignancy and for therapeutic reasons to restore growth and development in children with injured thyroid glands. It can be concluded that though the acute effects of exposure to large amounts of radionuclides taken internally may be negligible the possibility of serious late effects of injury to the thyroid gland is of considerable importance. There has been no indication in the Marshallese that the bone seekers such as ^{90}Sr or other radionuclides absorbed have produced any significant effects.

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Legends

Figure 1 Map of fallout area, Marshall Islands, March 1, 1954 (neg. 8-142-58)

Figure 2 Rongelap Village today - The old village was completely rebuilt. (no neg.#)

Figures 3 through 15 - See Atomic Medicine 4th Edition 1964

Figure 3 Chapter 12, Figure 1

Figure 4 Chapter 12, Figure 2

Figure 5 Chapter 11, Figure 1

Figure 6 Chapter 12, Figure 3

Figure 7 Chapter 8, Figure 6

Figure 8 Chapter 8, Figure 7

Figure 9 Chapter 8, Figure 8

Figure 10 Chapter 12,Figure 4

Figure 11 Chapter 12, Figure 6

Figure 12 Chapter 12, Figure 7

Figure 13 Chapter 12, Figure 8

Figure 14 Chapter 12, Figure 9

Figure 15 Chapter 12, Figure 11

Figure 16 Self-explanatory. (neg. # 6-951-66)

Figure 17 Two-hit chromosome aberrations in exposed Marshallese. Top: arrow points to dicentric form; bottom: arrow points to ring form. (neg.#11-1540-

Figure 18 Pigmented nevus-like lesions in previous "beta burn" area of neck(No. 78). (no neg.#

Figure 19 Depression of blood elements in Rongelap exposed people compared with average counts of unexposed people. (neg. # 11-280-66)

Figure 20 Self-explanatory. (neg. # 1-1054-63)

Figure 21 Two boys, age 12, showing greated growth retardation. Both boys became hypothyroid with atrophy of the thyroid gland (Subjects Number 3 and 5, see Figure 26). (neg. # CN 4-956-66)

Figure 22 Benign thyroid nodules at surgery. Sectioned gland shows multinodular, cystic and hemorrhagic nature of glands. (neg. # CN 3-103

Figure 23 Microscopic section of adenomatous nodule (21X). Note wide variation in size of follicles, some showing microfollicular tissue, others hyperplasia and some colloid cysts. (neg.# 10-1020-65)

Figure 24 Gross appearance of thyroid cancer (white tissue). (Neg. # 9-1026-66)

Figure 25 Microscopic appearance of metastasis into local blood vessels of mixed papillary and follicular carcinoma in 40 year old woman (10X), from gross specimens seen in Figure 24. (neg. # CN 10-720-

Figure 26 Self-explanatory. (neg. # 11-762-66)

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