BioFactors 19 (2003) 121–130
IOS Press

Review

Role of iodine in antioxidant defence in thyroid and breast disease

Peter P.A. Smyth*
Iodine Study Unit, Department of Medicine and Therapeutics, and Conway Institute of Biomolecular and Biomedical Research, University College Dublin, Ireland

Received 7 July 2003
Revised 15 September 2003
Accepted 30 September 2003

Abstract. The role played in thyroid hormonogenesis by iodide oxidation to iodine (organification) is well established. Iodine deficiency may produce conditions of oxidative stress with high TSH producing a level of H_2O_2, which because of lack of iodide is not being used to form thyroid hormones. The cytotoxic actions of excess iodide in thyroid cells may depend on the formation of free radicals and can be attributed to both necrotic and apoptotic mechanisms with necrosis predominating in goiter development and apoptosis during iodide induced involution. These cytotoxic effects appear to depend on the status of antioxidative enzymes and may only be evident in conditions of selenium deficiency where the activity of selenium containing antioxidative enzymes is impaired. Less compelling evidence exists of a role for iodide as an antioxidant in the breast. However the Japanese experience may indicate a protective effect against breast cancer for an iodine rich seaweed containing diet. Similarly thyroid autoimmunity may also be associated with improved prognosis. Whether this phenomenon is breast specific and its possible relationship to iodine or selenium status awaits resolution.

Keywords: Antioxidant, thyroid, breast, iodine, thyroid antibodies

1. Introduction

Iodine was first described as a constituent of burned seaweed [1]. Although its major role in the human thyroid was identified by Baumann [2], it was not until 1927 that Sir Charles Harrington [3] reported that the major part of the thyroxine (T4) molecule (65.3% by weight) was made up of iodine. Most of the investigations of iodine status in humans and animals have been focused on the role of iodine in thyroid function. Relatively little attention has been devoted to its extra thyroidal roles, one of the most important of which is its function as an antioxidant in human systems including the eye, thyroid and the breast [4–8]. The antioxidant properties of dietary iodide depend on a series of redox reactions underlying the iodination of tyrosine leading to the formation of thyroid hormones [9–11].

*Address for correspondence: Dr Peter P.A. Smyth, Iodine Study Unit, Department of Medicine and Therapeutics, University College Dublin, Woodview, Belfield, Dublin 4, Ireland. Tel.: +353 1 7162049; Fax: +353 1 7161136; E-mail: ppa.smyth@ucd.ie.

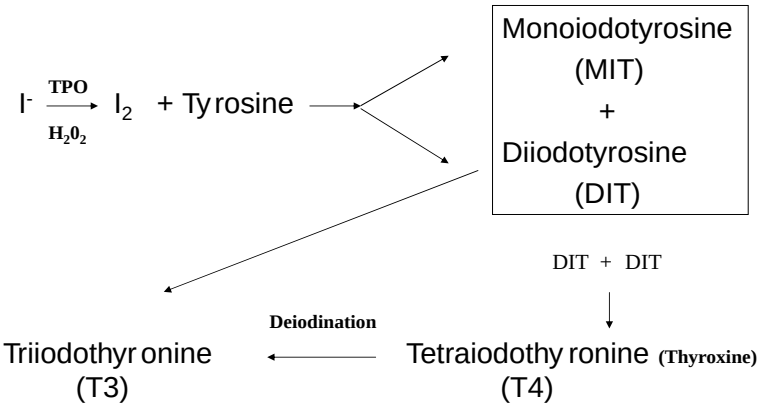

Fig. 1. Iodination of tyrosine and formation of thyroid hormones. TPO = Thyroid peroxidase.

2. Thyroid

As shown in Fig. 1, organification (oxidation) of iodide (I^-) to iodine (I_2) is accomplished by H_2O_2 catalysed by the enzyme thyroid peroxidase (TPO) and leads to the iodination of iodotyrosines and eventual formation of thyroid hormones triiodothyronine (T3) and thyroxine (T4). Since H_2O_2 is a major oxidant in the body, the more that is used up in the oxidation of I^-, the less is available for other potentially damaging oxidative processes and hence the role of I^- as an antioxidant. Provision of substrate H_2O_2 in the thyroid occurs via TSH mediated NADPH oxidase induction [12] and through the dismutation of superoxide (O_2^-) radicals thus formed, by the enzyme superoxide dismutase (SOD). While the antioxidant enzyme SOD enhances the rate of iodination in the thyroid [13], H_2O_2 is removed by antioxidative enzymes, principally those of the glutathione peroxidase (GPx) family [14] but also catalase. TSH exerts two principal effects on the thyroid gland. The best understood is a stimulus to produce thyroid hormones with a second function being the promotion of thyroid cellular growth [15]. The action of TSH on the thyroid follicular cell is mediated via intracellular signalling systems including the G protein linked cAMP and phosphoinositide cascades [15,16]. These signalling systems lead to TPO induction which, as previously stated, catalyses the oxidation of I^- to I_2. This oxidation requires the presence of an oxidizing agent H_2O_2 which is generated as a result of NADPH oxidation to NADP [17,18]. The oxidation of NADPH and therefore the generation of H_2O_2 is mediated by the recently described thyroid oxidases (ThOX1 and ThOX2) [19].

It is the action of H_2O_2 and other reactive oxygen species (ROS) that produce oxidative damage in the thyroid which in normal circumstances is protected through the action of the selenium (Se) containing antioxidative enzymes, the GPx family [14]. Oxidative damage to the thyroid is more severe in iodine deficiency where the gland is under increased stimulation by TSH resulting in excessive H_2O_2 production within the cells with relatively little substrate I^- to be oxidised. Se deficiency causes a deficit in GPx with a failure to remove H_2O_2, increased oxidative stress and thyroidal damage [17]. A combination of Se and I^- deficiency can lead to brain damage in the fetus or oxidative damage to DNA with the possibility of an increased incidence in thyroid malignancies [21,22].

NADPH oxidation resulting in H_2O_2 production is the rate limiting step for both iodination and the supply of NADP+ for the pentose phosphate pathway [17,18]. Interestingly inhibition of NADPH dependent H_2O_2 generation and thus of thyroid hormonogenesis forms a central feature of the mode of action of the antithyroid drugs propylthiourea (PTU) and methylmethimazole (MMI). PTU is a highly

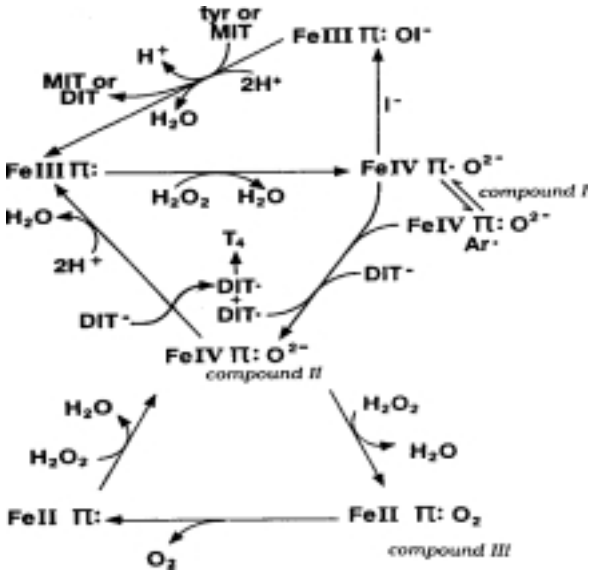

Fig. 2. Free radical involvement in thyroid hormonogenesis. Tyr = Tyrosine; MIT = Monoiodotyrosine; DIT = Diiodotyrosine; T4 = Thyroxine; (Fe III Π:) = porphyrin Π cation radical residing on the heme group of the thyroid peroxidase (TPO) molecule. Source: Bikker, H., Dissertation for PhD thesis, University of Amsterdam, 1996.

efficient scavenger of hydroxyl radicals [23] while both drugs inhibit TPO and NADPH driven H_2O_2 production [24]. Therefore both PTU and MMI can be termed antioxidant agents at least *in vitro* [23].

Although the greatly simplified reactions shown in Fig. 1 reflect what occurs in thyroid hormonogenesis, the actual pathways are more complex. A number of possible mechanisms through which iodination could take place have been postulated, of which the favoured was free radical formation [10]. A series of steps through which free radical mediated iodination might proceed are summarized in Fig. 2 for whose design I am grateful to J.J.M. de Vijlder, Amsterdam. This diagram is based on published findings [10,25,27]. TPO is a large ($\sim$ 105 kDa) heme containing glycoprotein that catalyses both iodination and iodotyrosine coupling in the thyroid gland [10]. The heme groups on the TPO molecule represented as a porphyrin Π cation radical (Fe III Π:) are oxidised by H_2O_2 formed principally through the action of the NADPH oxidase system at the thyroid follicular cell apical membrane to the Fe IV form giving up an electron to form superoxide (O_2^-) radicals (Fe IV $\Pi \cdot O_2^-$). Oxidation of native TPO by a slight excess of H_2O_2 in the presence of both I^- and Tg leads to the formation of Compound I, containing a porphyrin Π cation radical [11]. Compound I is isomerized to a protein radical form in which an electron is transferred from a nearby aromatic amino acid to the porphyrin ring. This compound is reduced by one electron to compound II. In this reaction diiodotyrosine (DIT^-), present as anion at physiological pH because the pK of DIT is 6.5, can provide this electron, and a DIT radical is formed [27]. Compound II, containing a Fe(IV) heme group, is further reduced by one electron to native Fe(lII) TPO, also producing a DIT radical. Two DIT radicals (in Tg) are able to couple, if they are located in the right position, and form T4. The structure of Tg is important in the successful catalysis of this reaction. An alternative iodinating mechanism suggested by Taurog [10] would involve the oxidized Fe IV $\Pi \cdot O_2^-$ giving up another electron to react with I^- to yield a complex with the OI^- (hypoiodite) ion, which in turn breaks down to yield I^+ (iodinium ion), which acts as the iodinating intermediate by attaching itself to a tyrosine molecule yielding monoiodotyrosine (MIT) and subsequently diiodotyrosine (DIT). The actual iodination species

potentially involved in formation of iodotyrosines are many and varied including, I^-, I^+ (iodinium), I_2, I^0 (iodine free radical), IO^- (hypoiodite), H_2IO^+ (hypoiodous acidinium ion), IO_3^- (iodate) [11].

A role for iodine in the evolutionary process has been postulated on the basis that in moving from the relatively iodine rich sea to the more iodine deficient land organisms had to develop systems such as the thyroid gland to provide a reservoir to permit survival in the iodine poor terrestrial environment [8]. While organisms moving from the iodine rich sea to the iodine poor land need mechanisms to trap iodide, they also face the hazard of having to deal with higher amounts of atmospheric O2 which in its various forms can be cytotoxic. The so called stress reaction to O_2 can result from the presence of reactive oxygen species (ROS) such as superoxide radicals (O_2^-) and H_2O_2. ROS can inactivate many enzymes and are a feature of lipid peroxidation and DNA damage and have been shown to be associated with carcinogenesis [28].

Early work on the stress effects of O_2 showed that removal of the thyroid gland decreased the toxic effects of O_2 while the administration of T4, cortisone or adrenaline made them worse [29]. Thyroid hormones are known to play a major part in the regulation of mitochondrial oxidative metabolism with overt hyperthyroidism causing enhanced oxidative metabolism with consequently reduced lipid and lipoprotein plasma levels while overt hypothyroidism results in reduced oxidative metabolism and markedly increased lipid and lipoprotein levels [30,31]. Iodine can react with double bonds on lipids such as polyunsaturated fatty acids rendering them less reactive to ROS. Polyunsaturated fatty acids such as arachidonic acid which is known to play a role in intracellular signalling in the thyroid contains four double bonds and can be easily oxidised and thus contribute to increased lipid peroxidation [32]. It has been postulated that formation of iodolipids such as iodolactones or iodoaldehydes represents a form of thyroidal autoregulation [33] which may be the mode of action of iodide inhibition of thyroidal function in the Wolff-Chaikoff effect [6,34,35]. While lower doses of iodide are necessary substrates for TPO mediated conversion into I_2, iodinated compounds (so called XI) at high doses may exert inhibitory effects on adenylate-cyclase, NADPH-oxidase and TPO activities [6,35]. This effect seems to require oxidation of I^- to I_2 as inhibitors of TPO or I^- trapping can reverse the inhibitory effect [35]. It is interesting to speculate if such compounds are involved in the reported down regulation of the sodium iodide symporter (NIS) by high doses of iodide which is also a feature of the Wolff-Chaikoff effect [36].

Iodide may act as an antioxidant by reducing the sensitivity of the thyroid gland to TSH as suggested by Bray [37] thus diminishing both T4 and H_2O_2 production. It has been demonstrated that even low to moderate (1–10 μM) doses of iodide can inhibit a series of TSH mediated thyroidal events including cAMP production, TPO and NIS expression in both human and dog thyroids [36,38]. Excess iodide can interfere with iodination of thyroglobulin within the thyroid gland thus inhibiting thyroid hormone formation. This forms the basis for the Wolff-Chaikoff effect [34]. Such inhibition is usually of a transient nature with normal thyroid hormone production being resumed, the so called "escape" from the Wolff-Chaikoff effect. It has also been postulated that production of iodinated compounds could form the basis for the reduction of the hypervascularity and hyperplasia produced by administration of high doses of iodide [39]. A pro-oxidant effect of excess iodide on thyroid cells leading to apoptosis was however demonstrated by the characteristic DNA fragmentation pattern and as described above seems to require oxidation of I^- to I_2 as its cytotoxic effects could be blocked by the TPO inhibitor propylthiouracil (PTU) [35]. The probability that I^- induced thyroid cellular apoptosis was related to free radical formation was supported by the demonstration of a significant increase in lipid peroxidation following I^- treatment [35]. This is in agreement with one of the possible mechanisms for free radical induced cytotoxicity in the thyroid suggested by Denef et al. [6]. Apoptosis is not the only pathway through which I^- induced cytotoxicity can be mediated as both thyroidal apoptosis and necrosis were implicated

with necrosis predominating in goiter development and apoptosis during iodide induced involution [40]. These workers attributed the necrotic effect to free radical formation which was potentiated in vitamin E deficient rats having reduced antioxidative protection (increased malondealdehyde ; MDA) reflecting increased lipid peroxidation and decreased Se containing GPx. The cytotoxic effect of excess iodide may depend on the relative abundance of Se and Fe in the thyroid , at least in conditions of iodine deficiency where TSH stimulated H_2O_2 is abundant, as it has been shown that necrosis produced in selenium deficient rats by H_2O_2 and infiltration by mononuclear cells was not observed in selenium replete animals [41]. This effect is presumably due to the failure to produce selenium containing antioxidative enzymes such as GPx [14,42]. Similarly Fe, known to be an intregal part of the heme portion of the TPO molecule [43], could limit removal of potentially cytotoxic H_2O_2 although this has not been established.

The iodine rich cardiac antiarrythmic drug amiodarone which has been reported to induce either hypothyroidism or hyperthyroidism in humans can also produce ultrastructural features of necrosis or apoptosis in rat thyroids [44]. As with the Wolff-Chaikoff effect such cytotoxicity can be prevented by inhibition of TPO, suggesting the requirement for iodinated compounds [35]. Indeed oxidative stress could explain an increase in malondealdehyde (MDA), a product of lipid peroxidation in iodine deficient glands [45] and the absence of toxicity of an identical iodine dose reaching iodine/thyroglobulin-replete glands. Oxidative stress also provides an explanation for the hypothyroidism (myxedematous cretinism) described in combined iodide and selenium deficiency, a situation characterised by low H_2O_2 detoxification reflecting the absence of selenium containing glutathione peroxidase (GPx) activity [46]. Administration of Se before correction of the iodine deficiency can disimprove the hypothyroidism by increasing T4 breakdown by Se containing deiodinase enzymes. It is therefore important that iodine supplementation precede that of Se. Deficiency of Se is associated with autoimmune thyroid disease (AITD) perhaps as a result of increased inflammatory activity arising from decreased activity of Se containing antioxidative enzymes. Selenium supplementation or selenomethionine treatment in patients with AITD has been reported to decrease thyroid peroxidase antibody (TPO Ab) concentrations [47,48] thus enhancing immunocompetence without affecting thyroid hormone levels.

The postulate that I^- itself exerts a significant antioxidant effect has been advanced for many years [8]. Indeed the antioxidant effect of NaI levels as low as 15 μM have been shown to be equivalent to that of the established antioxidant ascorbic acid (50 μM) [49]. The use of iodine rich brines or seaweeds as thalassotherapy or balneotherapy in health spas has been well established for many centuries [7]. Beneficial effects of such treatments in the area of cardiac and respiratory disease, thyroid function, arteriosclerosis, diabetes mellitus and eye diseases have received considerable attention [5,49,50].

3. Breast

The antioxidant properties of iodide described for the thyroid also apply to other tissues having the ability to concentrate iodide. These include the salivary glands, gastric mucosa and mammary glands [51,52]. Although TSH has no known role in promoting I^- uptake into mammary cells, these cells have been shown to possess the sodium iodide symporter (NIS) [53–54]. Uptake of I^- into mammary cells can be promoted by prolactin and combinations of hormones (prolactin, oxytocin, estrogens) known to be involved in lactation [54,55]. As well as promoting NIS expression, prolactin enhances expression of a second I – transporter Pendrin which in the thyroid facilitates I^- transport from the apex of the follicular cell into the follicular lumen and facilitates I^- accumulation in milk in the lactating mammary gland [56] . Although iodoprotein has been detected in breast tissue [57], it is not known if prolactin has a role in facilitating such iodinations. Free radicals have been associated with carcinogenesis in many

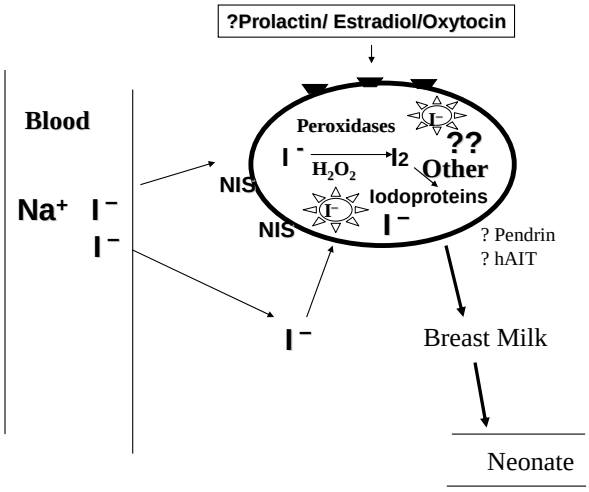

Fig. 3. Uptake and efflux of I^- in the mammary gland. NIS = Sodium iodide symporter; hAIT = Human apical iodide transporter.

organs including the human breast [58–60]. Increased serum levels of antioxidants have been associated with reductions in breast cancer risk [61] while increases in the activity of the antioxidant enzymes SOD, catalase and GPx have also been reported in in both malignant breast tumours and benign breast disease, which has been suggested to represent a compensatory response to increased lipid peroxidation as evidenced by parallel increases in MDA levels [62].

A role for iodide as an antioxidant possibly through a protective action of iodolipids as described for the thyroid has been suggested [64–66]. This is on the basis of a shared iodide concentrating mechanism in both thyroid and breast as well as a requirement for an iodide oxidation system to provide for the formation of iodoamino acids leading to thyroid hormone formation in the thyroid and to iodinated milk proteins by the breast necessary for neonatal nutrition [50–52]. Figure 3 shows in cartoon form the uptake of I^- by the breast and its incorporation into iodoproteins. When taken into the breast I^- is incorporated into lactoproteins presumably as a result of organification into I_2 by lactoperoxidases [57,66]. These iodoproteins together with free I^- are secreted in breast milk. As mentioned elsewhere in this communication, I^- may also be incorporated into iodolipids such as iodolactones or iodoaldehydes which in the thyroid have been shown to posess antiproliferative properties. To date there is no evidence that a similar effect is produced in the breast.

Although there is no direct evidence that I^- acts as an antioxidant in the breast, increased rates of breast cancer have been reported in iodine deficient populations [67]. Thyroid enlargement as measured by ultrasound has been reported in a significant number of patients with breast cancer compared to controls from the same area [68]. Iodine deficiency has also been linked to increased fibrosis and adenosis of the mammary gland and administration of iodine has been used in the treatment of breast pain [65,69]. It has also been suggested that a combined I^-/Se deficiency may facilitate the development of breast cancer [63].

An anticarcinogenic role for iodine in experimental animals has been suggested by the work of Funahashi et al. [70] who found that administration of Lugol's iodine or iodine rich Wakame seaweed to rats treated with the carcinogen dimethyl benzanthracene (DMBA) suppressed the development of mammary tumours. In further studies the same group [71] demonstrated that seaweed induced apoptosis in human breast cancer cells had a stronger effect than fluorouracil, a chemotherapeutic agent used

to treat breast cancer. This finding led the authors to speculate that "seaweed may be applicable for prevention of breast cancer ?" [72]. This hypothesis is in accord with the relatively low breast cancer rate reported in Japan [73] where the normal diet is seaweed rich and with increasing breast cancer rates in Japanese women who emigrate [74] or consume a western style diet [75]. Interestingly this finding applies to rates of breast cancer in both males and females [76]. This evidence favours the low rate of breast cancer being environmental rather than genetic in origin. One of the main dietary differences between Japanese and Western women is the consumption of large amounts of iodine rich seaweeds, the former yielding a dietary iodine intake of several mg/day in Japanese women compared to μg quantities in western women [63]. As with the thyroid, the antioxidant potential of I^- may require its oxidation to I_2. Indeed Eskin et al. [77] have postulated that normal physiological function of mammary tissue requires I_2.

Some support for a role for iodine in the human breast is provided by our own findings [53] which showed that tissue iodine levels were relatively low in patients with breast cancer compared to normal tissues or benign breast tumours by fibroadenomata. These findings coincided with decreased expression of the human sodium iodised symporter (NIS) in breast cancer patient tissues [78]. An association between various thyroid disorders and breast cancer has been suggested in many publications [79,80]. However, there is considerable disagreement concerning this linkage. A number of reports have demonstrated an association of autoimmune thyroid disease with breast cancer [81–84]. Despite these reports a recent meta analysis [85] showed a lack of any association between Hashimoto's thyroiditis and breast cancer. In common with reports from our own laboratory [83] showing that TPOAb positivity in patients with breast cancer was associated with better disease free and overall outcomes, an increased prevalence of TPOAb and better diseases outcome has also been reported both basally and following interferon gamma treatment of renal cell carcinoma [86]. Preliminary findings indicated that the prevalence of TPOAb as measured by sensitive radioimmunoassay was significantly greater in breast cancer patients than in controls or those with diverse malignancies [87]. While this evidence points to an involvement of thyroid autoimmunity in the natural history of breast cancer, its exact role, breast specificity or possible association with reactive oxygen species remains unclear. Also awaiting elucidation is a possible role for I or Se prophylaxis and the consequences of impaired transport and incorporation of iodine into mammary tissues.

References

[1] M.B. Curtois, Decouvert d'une substance nouvelle dans le varech, *Ann. de Chemie* **88** (1813), 304.
[2] E. Baumann, Ueber das normale Verkommen von Jod im Thierkorper, *Ztschr Physiol. Chemie* **21** (1895), 319.
[3] C.R. Harrington and G. Barger, Chemistry of thyroxine 111. Constitution and synthesis of thyroxine, *Biochem J* **21** (1927), 169.
[4] E.F. Elstner, R. Adamczyk, R. Kromer and A. Furch, The uptake of potassium iodide and its effects as an antioxidant in isolated rabbit eyes, *Ophthalmologica* **191** (1985), 122–126.
[5] G. Rieger, R. Winkler, W. Buchberger and M. Moser, Iodine distribution in a porcine eye model following iontophoresis, *Ophthalmologica* **209**(2) (1995), 84–7.
[6] J.F. Denef, M.C. Many and M.F. van den Hove, Iodine-induced thyroid inhibition and cell necrosis: two consequences of the same free-radical mediated mechanism? *Molecular and Cell Endo* **121** (1996), 101–103.
[7] R. Winkler and M. Klieber, Important results of about 45 years balneo-medical research in Bad Hall, *WienMedWorchenschrSupp* **148** (1998), 3–11.
[8] S. Venturi, F.M. Donati, M. Venturi, A. Venturi, L. Grossi and A. Guidi, Role of Iodine in Evolution and Carcinogenesis of Thyroid, Breast and Stomach, *Advances in Clinical Pathology* **4** (2000), 11–17.
[9] A. Taurog, M.L. Lothrop and R.W. Estabrook, Improvements in the isolation procedure for thyroid peroxidase: Nature of the heme prosthetic group, *Arch Biochem Biophys* **139** (1970), 221.

[10] A. Taurog, Hormone synthesis: thyroid iodine metabolism, in: *Werner and Ingbar's The Thyroid*, L. Braverman and R.D. Utiger, eds, Philadelphia: Lippincott Co, 1996, pp. 47–81.
[11] L.J. Degroot and H. Niepomniszcze, Biosynthesis of thyroid hormone: Basic and Clinical Aspects, *Metabolism* **26** (1977), 665–718.
[12] J.E. Dumont, F. Lamy, P. Roger and C. Mainhault, Physiological and pathological regulation of thyroid cell proliferation and differentiation by thyrotropin and other factors, *Physiol Reviews* **72** (1992), 667–697.
[13] K. Yamamoto and L.J. DeGroot, Participation of NADPH-cytochrome c reductase in thyroid hormone biosynthesis, *Endocrinology* **96** (1975), 1022.
[14] M. Birringer, S. Pilawa and L. Flohe, Trends in selenium biochemistry, *Nat Prod Rep* **6** (2002), 693–718.
[15] P.P. Roger, D. Christophe, J.E. Dumont and I. Pirson, Characterization of ThOX proteins as components of the thyroid H(2)O(2)-generating system, *Eur J Endocrinol* **137** (1997), 579–598.
[16] L.D. Kohn, K. Suzuki, M. Nakazato, I. Royaux and E.D. Green, Effects of thyroglobulin and pendrin on iodide flux through the thyrocyte, *Trends Endocrinol Metab* **12** (2001), 10–16.
[17] B. Corvilain, J. van Sande, E. Laurent and J.E. Dumont, The H_2O_2-generating system modulates protein iodination and the activity of the pentose phosphate pathway in dog thyroid, *Endocrinology* **128** (1991), 779–785.
[18] D.P. Carvalho, C. Dupuy, Y. Gorin, O. Legue, J. Pommier, B. Haye and A. Virion, The Ca^{++} and reduced nicotinamide adenine dinucleotide phosphate-dependent hydrogen peroxide generating system is induced by thyrotropin in porcine thyroid cells, *Endocrinology* **137**(3) (March 1996), 1007–1012.
[19] X. De Deken, D. Wang, J.E. Dumont and F. Miot, Characterization of ThOX proteins as components of the thyroid H(2)O(2)-generating system, *Exp Cell Res* **273** (2002), 187–196.
[20] B. Corvilain, B. Contempre, A.O. Longombe, P. Goyens, C. Gervy-Decoster, F. Lamy, J.B. Vanderpas and J.E. Dumont, Selenium and the thyroid: how the relationship was established, *Am J Clin Nutr* **57**(2 Suppl) (Feb 1993), 244S–248S.
[21] B. Giray and F. Hincal, Oxidative DNA base damage, antioxidant enzyme activities and selenium status in highly iodine-deficient goitrous children, *Free Radic Res* **36** (2002), 55–62.
[22] Y. Hasegawa, T. Takano, A. Miyauchi, F. Matsuzuka, H. Yoshida, K. Kuma and N. Amino, Decreased expression of catalase mRNA in thyroid anaplastic carcinoma, *Jpn J Clin Oncol* **33** (2003), 6–9.
[23] M. Hicks, L.S. Wong and R.O. Day, Antioxidant activity of propylthiouracil, *Biochem Pharmacol* **43** (1992), 439–444.
[24] A.C. Ferreira Freitas, L. de Carvalho Cardoso, D. Rosenthal and D.P. de Carvalho, Thyroid Ca2+/NADPH-dependent H_2O_2 generation is partially inhibited by propylthiouracil and methimazole, *Eur J Biochem* **270** (2003), 2363–2368.
[25] H. Bikker, *Dissertation for PhD thesis*, University of Amsterdam, 1996.
[26] A. Taurog and M. Wall, Proximal and Distal Histidines in Thyroid Peroxidase: Relation to the Alternatively Spliced Form, $TPO^{-}2$, *Thyroid* **8** (1998), 185–191.
[27] J.J.M. De Vijlder and M.T. den Hartog, The reason why the thyroid secretes mainly thyroxine. 11th International Thyroid Congress, Toronto Canada, 1995, S-162.
[28] H.E. Seifried, S.S. McDonald, D.E. Anderson, P. Greenwald and J.A. Milner, The antioxidant conundrum in cancer, *Cancer Res* **63** (2003), 4295–4298.
[29] R. Gerschman, D.L. Gilbert, S.W. Nye, P.W. Nadig and W.O. Fenn, Role of adrenalectomy and adrenal cortical hormones in oxygen poisoning, *Am J Physiol* **179** (1954), 115–118.
[30] K. Asayama and K. Kato, Oxidative muscular injury and its relevance to hyperthyroidism, *Free Rad Biol Med* **8** (1990), 293–303.
[31] F. Costantini, S.D. Pierdomenico, D.D. Cesare, P. De Remigis, T. Bucciarelli, G. Bittolo-Bon, G. Cazzolato, G. Nubile, M.T. Guagnano, S. Sengi, F. Cuccurullo and A. Mezzetti, Effect of Thyroid Function on LDL Oxidation, *Arterioscler Thromb Vasc Biol* **18** (1998), 732–737.
[32] A. Bonanome, A. Pagnan, S. Biffanti, A. Opportuno, F. Sorgato, M. Dorella, M. Maiorino and F. Ursini, Effect of dietary monounsaturated and polyunsaturated fatty acids on the susceptibility of plasma low density lipoproteins to oxidative modification, *Arterioscler Thromb* **12** (1992), 529–533.
[33] A. Dugrillon, Iodolactones and iodoaldehydes-mediators of iodine in thyroid autoregulation, *Exp Clin Endocrinol Diabetes* **104**(4) (1996), 41–45.
[34] J. Wolff and I.L. Chaikoff, Plasma inorganic iodide as a homeostatic regulator of thyroid function, *J Biol Chem* **174** (1948), 555–560.
[35] M. Vitale, T. Di Matola, F. D'Ascoli, S. Salzano, F. Bogazzi, G. Fenzi, E. Martino and G. Rossi, Iodide excess induces apoptosis in thyroid cells through a p53-independent mechanism involving oxidative stress, *Endocrinology* **141** (2000), 598–605.
[36] N. Uyttersprot, N. Pelgrims, N. Carrasco, C. Gervy, C. Maenhaut, J.E. Dumont and F. Miot, Moderate doses of iodide *in vivo* inhibit cell proliferation and the expression of thyroperoxidase and Na+/I− symporter mRNA's in dog thyroid, *Molecular and Cellular Endocrinology* **131** (1997), 195–203.
[37] G.A. Bray, Increased sensitivity of the thyroid in iodine-depleted rats to the goitrogenic effects of thyrotropin, *J Clin. Invest.* **47** (1968), 1640–1647.

[38] J.R. Sherwin and W. Tong, Iodide-induced suppression of thyrotropin-stimulated cyclic amp production and iodinating activity in thyroid cells, *Biochimica et Biophysica Acta* **404** (1975), 30–39.
[39] M.A. Pisarev and M.E. Itoiz, Action of KI on stimulated thyroid protein biosynthesis, *Endocrinology* **90**(5) (May 1972), 1409–1412.
[40] J.F. Mutaku, J.F. Poma, M.C. Many, J.F. Denef and M.F. van den Hove, Cell necrosis and apoptosis are differentially regulated during goiter development and iodine-induced involution, *Journal of Endocrinology* **172** (2002), 375–386.
[41] B. Contrempre, J.F. Denef, J.E. Dumont and M.C. Many, Selenium deficiency aggravates the necrotizing effects of a high iodide dose in iodine deficient rats, *Endocrinology* **132** (1993), 1866–1868.
[42] M.B. Zimmermann and J. Kohrle, The Impact of Iron and Selenium Deficiencies on Iodine and Thyroid Metabolism: Biochemistry and Relevance to Public Health, *Thyroid* **12** (2002), 867–878.
[43] L. Fayadat, P. Niccoli-Sire, J. Lanet and J.L. Franc, Role of heme in intracellular trafficking of thyroperoxidase involvement of H_2O_2 generated at the apical surface of thyr cells in autocatalytic covalent heme binding, *J Biol Chem* **274** (1999), 10533–10538.
[44] F. Bogazzi, L. Bartalena, M. Gasperi, L.E. Braverman and E. Martino, Various Effects of Amiodarone on Thyroid Function, *Thyroid* **11** (2001), 511–519.
[45] M.C. Many, J. Papadopolos, C. Martin, I. Colin and J.R. Denef, Iodine induced cell damage in mouse hyperplastic thyroid is associated to lipid peroxidation, in: *Progress in Thyroid Research*, A. Gordon, K. Gross and G. Hennemann, eds, 18 Ilkema, Rotterdam, 1991, pp. 635–636.
[46] B. Contrempre, J.E. Dumont and N. Bebe et al., Effect of selenium supplementation in hypothyroid subjects of an iodine and selenium deficient area: the possible danger of indiscriminate supplementation of iodine deficient subjects with selenium, *J Clin Endocrinol Metab* **73** (1991), 213–215.
[47] R. Gartner, B.C.H. Gasnier, J.W. Dietrich, B. Krebs and M.W.A. Angstwurm, Selenium Supplementation in Patients with Autoimmune Thyroditis Decreases Thyroid Peroxidase Antibodies Concentrations, *J Clin Endo Metab* **87** (2002), 1687–1691.
[48] L.H. Duntas, E. Mantzou and D.A. Koutras, Effects of a six month treatment with selenomethionine in patients with autoimmune thyroiditis, *European Jour Endo* **148** (2003), 389–393.
[49] R. Winkler, S. Griebenow and W. Wonisch, Effect of Iodide on Total Antioxidant Status of Human Serum, *Cell Bio and Function* **18** (2000), 143–146.
[50] F. Tatzber, S. Griebenow, W. Wonisch and R. Winkler, Dual method for the determination of peroxide activity and total peroxides-iodide leads to a significant increase of peroxidase activity in human sera, *Analytical Biochemistry* **316** (2003), 147–153.
[51] C. Spitzweg, K.J. Harrington, L.A. Pinke, R.G. Vile and J.C. Morris, The Sodium Symporter and Its Potential Role in Cancer Therapy, *J of Clin Endo and Metab* **86** (2001), 3327–3335.
[52] I.L. Wapnir, M. van de Rijn, K. Nowels, P.S. Amenta, K. Walton, K. Montgomery, R.S. Greco, O. Dohan and N. Carrasco, Immunohistochemical Profile of the Sodium/Iodide Symporter in Thyroid, Breast, and Other Carcinomas Using High Density Tissue Microarrays and Conventional Sections, *The Journal of Clin Endo and Metab* **88** (2003), 1880–1888.
[53] M.T. Kilbane, R.A. Ajjan, A.P. Weetman, R. Dwyer, E.W.M. McDermott, N.J. O'Higgins and P.P.A. Smyth, Tissue Iodine Content and Serum Mediated 125I Uptake Blocking Activity in Breast Cancer, *Journal of Clinical Endocrinology and Endocrinology* **85** (2000), 1245–1250.
[54] U.H. Tazebay, I.L. Wapnir, O. Levy, O. Dohan, L.S. Zuckier, Q.H. Zhao, H.F. Deng, P.S. Amenta, S. Fineberg, R.G. Pestell and N. Carrasco, The Mammary Gland Iodide Transporter is Expressed During Lactation and in Breast Cancer, *Nat Med* **6** (2000), 871–878.
[55] J.A. Rillema, T.X. Yu and S.M. Jhiang, Effect of prolactin on sodium iodide symporter expression in mouse mammary gland explants, *Am J Physiol Endocrinol Metab* **279** (2000), E769–772.
[56] J.A. Rillema and M.A. Hill, Prolactin regulation of the pendrin-iodide transporter in the mammary gland, *Am J Physiol Endocrinol Metab* **284** (2003), E25–28. Epub 2002 Sep 11.
[57] J.M. Strum, P.C. Phelps and M.M. Mc Atee, Resting human female breast tissue produces iodinated proteins, *J Ultrastructure Research* **84** (1983), 130–139.
[58] N.F. Boyd and V. McGuire, The possible role of lipid peroxidation in breast cancer risk, *Free Rad Biol Med* **10** (1991), 185–190.
[59] H.J. Sipe Jr, S.J. Jordan, P.M. Hanna and R.P. Mason, The metabolism of 17 beta-estradiol by lactoperoxidase: a possible source of oxidative stress in breast cancer, *Carcinogenesis* **11** (1994), 2637–2643.
[60] M.A. Trush and T.W. Kensler, An overview of the relationship between oxidative stress and chemical carcinogenesis, *Free Rad Biol Med* **10** (1991), 201–209.
[61] S. Ching, D. Ingram, R. Hahnel, J. Beilby and E. Rossi, Serum Levels of Micronutrients, Antioxidants and Total Antioxidant Status Predict Risk of Breast Cancer in a Case Control Study, *J Nutrit* **132** (2002), 303–306.
[62] M.F. Polat, S. Taysi, M. Gul, O. Cikman, I. Yilmaz, E. Bakan and F. Erdogan, Oxidant/antioxidant status in blood of patients with malignant breast tumour and benign breast disease, *Cell Biochemistry and Function* **20** (2002), 327–331.

[63] S.A. Cann, J.P. van Netten and C. van Netten, Hypothesis: Iodine, selenium and the development of breast cancer, *Cancer Causes and Control* **11** (2000), 121–127.
[64] S. Venturi, Is there a role for iodine in breast diseases? *"The Breast" Journal* **10** (2001), 379–382.
[65] B.A. Eskin, Iodine metabolism and Breast Cancer, *Trans NY Acad Sci* **11** (1970), 911–947.
[66] N.M. Shah, B.A. Eskin, T.B. Krouse and C.E. Sparks, Iodoprotein formation by rat mammary glands during pregnancy and early postpartum period, *Proc Soc Exp Biol Med* **181** (1986), 443–449.
[67] G.M. Bogardus and J.W. Finley, Breast cancer and thyroid disease, *Surgery* **49** (1961), 461–468.
[68] P.P.A. Smyth, D.F. Smith, E.W.M. Mc Dermott, M.J. Murray, J.G. Geraghty and N.J. O'Higgins, A direct relationship between thyroid enlargement and breast cancer, *J Clin Endocr Metab* **81** (1996), 937–941.
[69] W.R. Ghent, B.A. Eskin, D.A. Low and L.P. Hill, Iodine replacement in fibrocystic breast disease, *Canadian J Surgery* **36** (1993), 453–459.
[70] H. Funahashi, T. Imai, Y. Tanaka, J. Tobinaga, M. Wada, T. Morita, F. Yamada, K. Tsukamura, M. Oiwa, T. Kikumori, T. Narita and T. Hiroshi, Suppressive effect of iodine on DMBA-induced breast tumor growth in the rat, *J Surg. Oncol.* **61** (1996), 209–213.
[71] H. Funahashi, Wakame Seaweed Suppresses the Proliferation of 7,12-Dimethylbenz(a)-anthracene-induced Mammary Tumours in Rats, *Jpn. J. Cancer Res.* **90** (1999), 992–997.
[72] H. Funahashi, T. Imai, T. Mase, M. Sekiya, K. Yokoi, H. Hayashi, A. Shibata, T. Hayashi, M. Nishikawa, N. Suda, Y. Hibi, Y. Mizuno, K. Tsukamura, A. Hayakawa and S. Tanuma, Seaweed Prevents Breast Cancer? *Jpn. J. Cancer Res* **92** (2001), 483–487.
[73] P. Pisani, D.M. Parkin, F. Bray and J. Ferlay, Estimates of the worldwide mortality from 25 cancers in 1990, *Int J Cancer* **83** (1999), 18–29.
[74] L. Le Marchand, L.N. Kolonel and A.M. Nomura, Breast cancer survival among Hawaii Japanese and Caucasian women. Ten year rates and survival by place of birth, *Am J Epidemiol* **122** (1985), 571–578.
[75] Y. Minami, A. Takano, Y. Okuno, A. Fukao, M. Kurihara and S. Hisamichi, Trends in the incidence of female breast and cervical cancers in Miyagi Prefecture, Japan, 1959–1987, *Jpn J Cancer Res* **87** (1996), 10–17.
[76] N. Tajima, H. Tsukuma and A. Oshima, Descriptive epidemiology of male breast cancer in Osaka, Japan, *J Epidemiol* **11** (2001), 1–7.
[77] B.A. Eskin, C.E. Grotkowski, C.P. Connolly and W.R. Ghent, Different Tissue Responses for Iodine and Iodide in Rat Thyroid and Mammary Glands, *Biological Trace Element Research* **49** (1995), 9–19.
[78] R.M. Dwyer, M.T. Kilbane, R.A. Ajjan, D.F. Smith, A.P. Weetman, E.W.M. Mc Dermott, N.J. Higgins and P.P.A. Smyth, The Sodium Symporter (NIS), Iodine and Breast Cancer, *Endo* **164** (2000), P400.
[79] M.B. Goldman, Thyroid diseases and breast cancer, *Epidemiol Rev* **12** (1990), 16–28.
[80] P.P.A. Smyth, The Thyroid and Breast Cancer: A Significant Association? *Ann Med* **29** (1997), 189–191.
[81] K. Itoh and N. Maruchi, Breast cancer in patients with Hashimoto's thyroiditis, *Lancet* **ii** (1975), 1119–1121.
[82] C. Giani, P. Fierabracci, R. Bonacci, A. Gigliotti, D. Campani, F. De Negri, D. Cecchetti, E. Martino and A. Pinchera, Relationship between Breast Cancer and Thyroid Disease: Relevance of Autoimmune Thyroid Disorders in Breast Malignancy, *J Clin Endocr Metab* **81** (1996), 990–994.
[83] P.P.A. Smyth, S.G. Shering, M.T. Kilbane, M.J. Murray and E.W.M. McDermott, Smith DF and O'Higgins NJ. Serum TPO autoantibodies, thyroid volume and outcome in breast carcinoma, *Journal of Clinical Endocrinology and Endocrinology* **83** (1998), 2711–2715.
[84] P.P.A. Smyth, Autoimmune Thyroid Disease and Breast Cancer: A Chance Association? *Journal of Endocrinological Investigation* **23** (2000), 42–43.
[85] N.J. Sarlis, L. Gourgiotis, F. Pucino and G.J. Tolis, *Lack of association between Hashimoto thyroiditis and breast cancer: A quantitive research synthesis* **1**(1) (2002), 35–41.
[86] A. Franzke, D. Peest, M. Probst-Kepper, J. Buer, G.I. Kirchner, G. Brabant, H. Kirchner, A. Ganser and J. Atzpodien, Autoimmunity Resulting From Cytokine Treatment Predicts Long-Term Survival in Patients With Metastatic Renal Cell Cancer, *J Clin Oncol* **17** (1999), 529–533.
[87] P.P.A. Smyth, C.G. Brennan, D. Kavanagh, D.F. Smith, F. Fleming, E.W.M. McDermott, A.D.K. Hill, N.J. O'Higgins, P. Barrett and C.P. Thompson, Serum TSH and thyroid autoantibodies in thyroidal and extrathyroidal disease, *Endocrine Abstracts* **5** (2003), P271.