SLC26A4 variations among Graves’ hyper-functioning thyroid gland

Hassen Hadj-Kacem, Rihab Kallel, Salima Belguith-Maalej, Mouna Mnif, Ilhem Charfeddine, Abdelmounem Ghorbel, Mohamed Abid, Hammad Ayadi and Saber Masmoudi

Abstract. Deleterious mutations of SLC26A4 cause Pendred syndrome (PS), an autosomal recessive disorder comprising goitre and deafness with enlarged vestibular aqueducts (EVA), and nonsyndromic hearing loss (NSHL). However, the SLC26A4 hyperactivity was recently associated with the emergence of autoimmune thyroid diseases (AITD) and asthma among human and mouse model. Here, by direct sequencing, we investigate the sequences of the 20 coding exons (2 to 21) of SLC26A4 and their flanking intron-exon junctions among patients affected with Graves’ disease (GD) hyperthyroidism. Ten mono-allelic variants were identified, seven of which are intronic and previously unreported. Two, c.898A>C (p.I300L) and c.1061T>C (p.F354S), of the three exonic variants are non synonymous. The p.F354S variant is already described to be involved in PS or NSHL inheritances. The exploration by PCR-RFLP of p.I300L and p.F354S variants among 132 GD patients, 105 Hashimoto thyroiditis (HT), 206 Healthy subjects and 102 families with NSHL have shown the presence of both variants. The p.F354S variation was identified both among patients (1 HT and 3 GD) and healthy subjects (n=5). Whereas, the p.I300L variant was identified only in GD patients (n=3). Our studies provide evidence of the importance of systematic analysis of SLC26A4 gene sequences on models other than deafness. This approach allows the identification of new variants and the review of the pathogenic effects of certain mono-allelic variants reported responsible for PS and NSHL development.

Keywords: Pendred syndrome, autoimmune thyroid disease, Graves’ disease, SLC26A4

1. Introduction

Since 1997 the genomic sequence of PDS (SLC26A4) gene was investigated to explain the inheritance of autosomal syndromic or isolated hearing loss among family and sporadic patients [1]. Biallelic mutations in the SLC26A4 gene lead to Pendred syndrome (PS), an autosomal recessive disorder characterized by sensorineural deafness, goiter, and impaired iodide organification [2]. The SLC26A4 gene encodes the pendrin protein which is an anion transporter that is expressed in the inner ear, the thyroid, the kidney, the placenta and the endometrium [3–7]. In the inner ear, pendrin has been found in the stria vascularis of the cochlea and in the endolymphatic duct and sac, where it functions as a Cl−/HCO3− exchanger [8]. In the kidney, pendrin is localized in the apical membrane of type-B intercalated cells and non-A, non-B intercalated cells of the cortical collecting ducts and connecting tubules, where it again acts as a Cl−/HCO3− exchanger regulating the acid-base status and chloride homeostasis [9]. In thyroid follicular cells, pendrin is expressed at the apical membrane [10]. Functional in vitro data and the impaired iodide organification observed in patients with PS support a role of pendrin as an apical iodide transporter.

In PS the thyroid symptoms are highly variable. Indeed, goiter is not a constant feature and can range
from a slight increase in thyroid size to a large multinodular goiter [11]. Anyway, the SLC26A4 mutation is often associated with hypo-functioning when thyroid affection is described.

In 2003, we reported the genetic involvement of SLC26A4 in the susceptibility to autoimmune thyroid disease (AITD) [12]. The hyper expression of pendrin at the apical membrane of Graves’ Disease (GD) thyrocytes was firstly described by Royaux et al. (2000). More recently, Yoshida A. et al. (2009) have shown the presence of anti pendrin auto-antibodies in the sera of patients affected with auto-immune thyroid diseases (AITD) [13]. In addition, recent studies in mouse models implicate SLC26A4 hyperactivity in asthma and chronic obstructive pulmonary disease (COPD) development [14–16]. Expression of pendrin in the lung increases in response to allergens and high concentrations of IL-13 [17,18]. Recently, in order to evaluate the association between SLC26A4 variants and asthma emergence, the investigation of asthma prevalence among PS patients (two mutant alleles) or subjects with zero and one mutant alleles of SLC26A4 gene was described [19].

Although the involvement of the SLC26A4 gene has been reported with several pathological models, the systematic screening of the coding sequence of the gene is conducted only among deaf patients usually having a normal or hypo-functionning thyroid gland. Here, by direct sequencing we investigate the exonic sequence of SLC26A4 among patient affected with Graves’ hyper-functioning thyroid gland and we identified ten variants.

2. Subjects and methods

2.1. AITD patients and controls

One hundred thirty two unrelated patients (101 women and 31 men) with GD and 105 unrelated patients (94 women and 11 men) with Hashimoto Thyroiditis (HT) were included in this study. Data gathered from the patient group were compared with those obtained from a control population of 206 unrelated healthy subjects (103 women and 103 men) originating from the same area with no clinical evidence or family history of AITD and inflammatory joint disease.

GD was diagnosed on the basis of clinical and laboratory evidence of hyperthyroidism requiring treatment, palpable diffuse goiter, high thyroid hormonal rates, positive anti-TSHR, antithyroid peroxidase (anti-TPO), and/or anti-thyroglobulin (anti-Tg) antibodies. HT was diagnosed by documented clinical and biochemical hypothyroidism requiring thyroid hormone replacement and presence of autoantibodies to thyroid peroxidase, with or without antibodies to thyroglobulin.

Twenty unrelated GD patients (gender: 16 women and 4 men, age at diagnosis: 36.8 ± 18, goitre: 95%, Graves’ ophthalmopathy: 90%, anti-Tg: 70%, anti-TPO: 70%) were randomly selected from the pool of GD patients in order to perform the sequencing of SLC26A4 gene exons and their flanking intron-exon junctions. Two patients (one man and one woman) extracted from the families already used in the linkage studies [12] were added to the sequencing project. All selected patients have no familial history of hearing loss.

2.2. Deaf patients

We analysed 102 Tunisian families in which severe to profound nonsyndromic (NSHL) is transmitted as an autosomal recessive trait. The medical history was obtained and all individuals were evaluated by clinical examination including otoscopic exploration and pure-tone audiometry. Syndromic forms and patients with suspected environmental cause of hearing impairment (HI) were excluded.

All experiments were undertaken with the understanding and written consent of each subject. This study conforms to The Code of Ethics of the World Medical Association and reviewed and approved by the local ethics committee.

2.3. PCR and direct sequencing

Genomic DNA was isolated from EDTA-containing whole blood using the standard phenol-chlorophorm extraction protocol. The 20 coding exons (numbered from 2 through 21) of the SLC26A4 gene (and their flanking intron-exon junctions) were amplified by polymerase chain reaction (PCR) from peripheral leukocytes using primers listed in the Table 1. For all reactions, the 50-µL reaction mixture contained about 200 ng of genomic DNA, 2.5 mmol/L MgCl₂, 0.2 mmol/L of each deoxynucleoside triphosphate (dNTP), 0.10 µmol/L of each primer, 1 × reaction buffer, and 1 U of Taq DNA polymerase (Fermentas, EU). The PCR products were purified by enzymatic treatment using 10U of ExonucleaseI (Fermentas, EU) and 1U of Shrimp Alcaline Phosphatase (Fermentas, EU) and sequenced by automated DNA sequencing.
Table 1

| Exon | Primer sequence | Fragment size |
|------|----------------|---------------|
| 2    | caggtgatcctgttctct | 418bp         |
| 3    | aggaccggagacaggaatgt | 338bp        |
| 4    | cacgacgaactgcgttcagtc | 295bp        |
| 5    | tgcaccaacctagttgtaaa | 375bp        |
| 6    | aacacctctagaccaactgt | 353bp        |
| 7    | tctctcactaacataacaccag | 332bp        |
| 8    | gtcgaactatagactttcagtc | 250bp        |
| 9    | ggcagctactgactagtctct | 250bp        |
| 10   | ttcctctcactaacataacaccag | 240bp        |
| 11   | aacctctagaccaactgt | 241bp        |
| 12   | cgcatttgttatattttagtgacg | 281bp        |
| 13   | ggtctctgatgccctcagtcgttgc | 240bp        |
| 14   | cccgtgcacctctcagtc | 240bp        |
| 15   | cgctgactgactgctgtctgc | 296bp        |
| 16   | ggtctctgatgccctcagtcgttgc | 250bp        |
| 17   | gaaatagtgtgaggttttgg | 400bp        |
| 18   | gcaacttcggcacaaccacaccag | 215bp        |
| 19   | cctctcactaacataacaccag | 215bp        |
| 20   | aacctctagaccaactgt | 235bp        |
| 21   | aaagactgacagacttaaagagaa | 235bp        |

analysis with fluorescence-labeled deoxyterminators (BigDye Terminator V3.1 Cycle Sequencing Kits, Applied Biosystems, Foster City, CA) according to the manufacturer’s recommendations (ABI3100–4 Genetic Analyser, Applied Biosystems, Foster City, CA).

2.4. PCR-RFLP

The −103 T/C (rs60284988), c.898A>C and c.1061T>C variants were explored by the polymerase chain reaction–restriction fragment length polymorphism method (PCR-RFLP) using the appropriate primers (Table 1). The −103 T/C transition on the untranslated exon 1 sequence of SLC26A4 gene was explored using the following primers: forward CCTTCGACCAAG-GTGTCTGC and reverse TTAAGAGTCCCATCGCAAC with introducing mutation in the forward sequence in order to create a BsrBI specific restriction site containing the “C” allele.

PCR amplification was performed as described above. Genotypes discriminations were achieved by fragments restrictions using BsrBI, MboII and MnlI (fermentas, EU) to explore −103 T/C, 1061T>C and 898A>C variants respectively. Digestion reactions were performed according to the provider protocols. To verify digestion reactions, the same procedure was performed on a commercial plasmid cloning vector (pUC19; New England Biolabs) containing 3 BsrBI, 8 MboII and 13 MnlI restriction sites and three different PCR fragments containing a single restriction site for each used restriction enzyme. Amplified products were resolved on 4% agarose gels. Subjects with the rare allele were sequenced as described above.

3. Results and discussion

Pendrin is a member of the anion transporter family SLC26, which mediates the exchange of anions including Cl−, HCO3−, OH−, I−, or formate [20], and is encoded by the SLC26A4 gene. Apically located pendrin [10] seems to be responsible for the efflux of iodide into the follicular lumen [21–23].

Mutations in SLC26A4 cause nonsyndromic hearing loss associated with an enlarged vestibular aqueduct (ns-EVA), also known as DFNB4 and PS, the most common type of autosomal-recessive syndromic deafness (up to 10%) [24,25]. PS seems to be linked to bi-allelic mutations of the SLC26A4 genes. ns-EVA is genetically more heterogeneous relative to PS, and although some cases show mono- or bi-allelic SLC26A4 mutations (on cis- or trans-position), other cases are not linked to the SLC26A4 locus. Since its characterization [1], about 200 allelic variants of the SLC26A4 gene have been described (www.healthcare.uiowa.edu/labs/pendredandbor and literature), all of which are located along the coding sequence, the splice sites, and in the noncoding exon 1 within the FOXII binding transcriptional regulatory elements [26]. In PS patients, pendrin impaired function at the thyroid level can result in goiter, defects in iodide organification, and hypothyroidism [11,27,28]. The variability of thyroid symptoms in PS is well described [24,29]. Moreover, SLC26A4 mutations associated with congenital hypothyroidism (CH), multinodular dyshormonogenetic goitre or goitrous CH are reported, even though they
are rare [30–32]. Unfortunately, independently to PS clinical evidence, the analysis of SLC26A4 genomic sequence among patients with thyroid disease is poor documented.

Here, with the aim to explain our previous genetic study [12] and in order to bring more clarity on the variability of thyroid affection under SLC26A4 mutations, we examine the variability of the SLC26A4 gene sequence among AITD patients. We started our project by direct sequencing of the exonic sequences of gene and their flanking intron-exon junctions among GD patients. The choice of GD was not random. Indeed, all the mutations described until now are responsible for a hypothyroid state. Thus, from a functional standpoint, the identification of allelic variants in patients suffering from hyper function of the thyroid gland is also attractive.

Exploration of SLC26A4 gene sequence in 20 Tunisian unrelated GD patients reveals 10 mono-allelic variants, seven of which are intronic and previously unreported (Table 2). However, no polymorphisms have been identified in patients extracted from AITD families already used in the genetic study [12]. Besides, the exploration of the −103 T/C transition (rs60284988) in the 5’UTR (exon1) of the SLC26A4 gene showed the absence of the “C” allele in all tested subjects. Three different exonic variants; two transversion in exon 7 (c.898A>C) and 12 (c.1368C>G) and one transition in exon 9 (c.1061T>C) were identified. The positive patient for c.1061T>C also displays a heterozygosis for c.304+24T>C and c.164+62G>C variants.

In this work, we focus on the non synonymous variants. In fact, the c.898A>C and c.1061T>C led to an amino acids substitution respectively at the positions 300 (p.I300L) and 354 (p.F354S) of the pendrin sequence (Fig. 1). The analysis of both variations by PCR-RFLP among patients (GD (n = 132) and HT (n = 105)) and healthy subjects (n = 206) identify 9 heterozygous subjects for the p.F354S variant, 3 GD, 1 HT and 5 healthy subjects (3 males and 2 females). Nevertheless, the p.I300L variation was detected only in 3 GD heterozygous patients. For the two variants, all identified patients were female with goitre, no Graves’ ophthlamopathy and no hearing loss family history. The absence of homozygous subjects for both variations reflects the weak frequencies of the rare alleles in the general population (around 1%). The exploration of both variants among 102 NSFHL Tunisian families confirms once again their rarities. Indeed, both variants are absent.

The analysis of the coding sequences of SLC26A4 gene (protein and mRNA) of 12 animals showed the conservation of I300 and F354 among all used species at protein and mRNA levels (A898 and T1061) (Figs 1 and 2).

Two putative topologies of human pendrine were reported in the literature with 12 transmembrane model (described on the Pendred/BOR homepage (http://www.healthcare.uiowa.edu/labs/pendredandbor/domains.htm)) or 15 transmembrane-segment models [33]. p.I300L and p.F354S were localised respectively in the S7 and S8 transmembrane segments of the first model and in S9 and S10 transmembrane segments of the second model.

The p.F354S was already described by four different studies of SLC26A4 sequence [34–37]. Blons et al. (2004) and Albert et al. (2006) attribute a pathogenic effect of this variant to explain syndromic or isolate hearing loss respectively among sporadic and familial appearances. Thyroid affection was described (hypothyroidism) when the compound heterozygosity effect with the p.Y530H mutation was detected [34]. Anyway, the F354S was never been described as a biallelic mutation. Recently, Dai et al (2009) attribute a functional effect for p.F354S substitution. In fact, the mutant protein expressed in Xenopus oocytes displayed selective reduction in relative rate of Cl\(^-\)/HCO\(_3\)^− exchange compared with similarly measured rates of

---

**Table 2**

| Nucleotide change | Exon/Intron | aa change | Genotype | Patient number |
|-------------------|-------------|-----------|----------|----------------|
| c.164+11C>G       | In 2        | −         | CG       | 1              |
| c.164+48A>T       | In 2        | −         | AT       | 1              |
| c.164+62G>C       | In 2        | −         | GC       | 1              |
| c.304+24T>C       | In 3        | −         | TC       | 2              |
| c.415+54C>A       | In 4        | −         | CA       | 2              |
| c.898A>C          | Ex 7        | I300L     | AC       | 1              |
| c.1061T>C         | Ex 9        | F354S     | TC       | 1              |
| c.1368C>G         | Ex 12       | A456A     | CG       | 1              |
| c.1614+8C>T       | In 14       | −         | CT       | 1              |
| c.1614+14T>G      | In 14       | −         | TG       | 1              |

---

---
Fig. 1. The p.I300L and p.F354S variants: electrochromatogramme of heterozygous GD patients and the conservation of 300 and 354 position among 12 animal protein sequences. The protein alignment was carried out using respectively the following references: Homo sapiens NP_000432.1, Pan troglodytes XP_519308.2, Macaca mulatta XP_001094049.1, Pongo abelii CAI30271.1, Canis Familiaris XP_540382.2, Bos Taurus XP_608706.3, Mus musculus NP_035997.1, Rattus norvegicus NP_062087.1, Monodelphis domestica XP_001363598.1, Danio rerio NP_001159387.1, Xenopus laevis NP_001098008.1, Gallus gallus XP_125419.2.

Fig. 2. The conservation of A898 and T1061 positions among 12 animal SLC26A4 mRNA sequences. The alignment was carried out using respectively the following references: Homo sapiens NM_000441.1, Pan troglodytes XM_519308.2, Macaca mulatta XM_001094049.1, Pongo abelii CR926479.1, Canis Familiaris XM_540382.2, Bos Taurus XM_608706.3, Mus musculus NM_011867.2, Rattus norvegicus NM_019214.1, Monodelphis domestica XM_001363561.1, Danio rerio NM_001165915.1, Xenopus laevis NM_001095359.1, Gallus gallus XM_425419.2.

Cl\(^{-}/\)Cl\(^{-}\) and Cl\(^{-}/\)I\(^{-}\) exchange. This finding emphasized the role of p.F354S in the inner ear and reduce its pathogenic effect in the thyroid gland function. However, using a cohort of 214 normal-hearing individuals of Spanish–Caucasian population, Pera et al. [37] have reported the identification of p.F354S and the absence of this variant among patient group. Our work suggests that the p.F354S variant seems to be a rare polymorphism.

Different to p.F354S, the pathogenic effect of p.I300L was never been investigated. This variant was reported in one family by the Molecular Otolaryngology Research Laboratories (MORL) (http://www.medicine.uiowa.edu/otolaryngology/MorlLab/SLC26A4) without any clinical information and as a personal communication from Prasad S. The absence of p.I300L among patients with HT (n = 105), deafness (n = 102) and healthy subjects (n = 206) suggests a potential role of p.I300L in the GD genetic susceptibility. The comparison between the expected genotypic distribution (under Hardy Weinberg equilibrium) and the observed data showed a significant difference (Fisher exact test \(p < 0.01\)). However, even if p.I300L has a contribution in the development of GD, its role should be minor and involves only a reduced number of patients (3/132). Anyway, even if the genetic of AITD is complex, the
involvement of SLC26A4 in its development is not excluded. Interestingly, autoanti-body recognizing Pendrin protein has recently been described in HT and, to a lesser extent in GD, using immunoblotting with patient sera [13]. On the other hand, the concurrence of PS, autoimmune thyroiditis, and simple goiter in one family has been described [38]. More recently, the association between PS and autoimmune hyper-functioning thyroid gland was reported, when the pathogenic effect of compound heterozygosity (1001+1G>A and 2015G>A base changes) within the SLC26A4 genomic sequence is suspect [39].

Although more than 20 exonic variants of the SLC26A4 gene have already undergone functional exploration [33], the pathogenic effects of promoter (regulation) and intronic (splice) variants on the gene and pendrin expression remain unexplored. Further, such investigation could provide clarifications on the contribution of the SLC26A4 gene in the development of certain complex diseases with population high prevalence such as AITD, hypertension and asthma. The considerable advances in sequencing techniques could enhance the consideration of some reported mono-allelic variants responsible for PS or NSHL.

Acknowledgments

This work was supported by the Ministère de l’enseignement supérieur et de la Recherche Scientifique (Tunisia).

References

[1] L.A. Everett, B. Glaser, J.C. Beck, J.R. Idol, A. Buchs, M. Heyman, F. Adawi, E. Hazani, E. Nassir, A.D. Baxevanis, V.C. Sheffield and E.D. Green, Pendred syndrome is caused by mutations in a putative sulphate transporter gene (PDS), Nat Genet 17 (1997), 411–422.

[2] W. Reardon and R.C. Trembath, Pendred syndrome, J Med Genet 33 (1996), 1037–1040.

[3] J.M. Bidart, C. Mian, V. Lazar, D. Russo, S. Filetti, B. Caillou and M. Schlumberger, Expression of pendrin and the Pendred syndrome (PDS) gene in human thyroid tissues, J Clin Endocrinol Metab 85 (2000), 2028–2033.

[4] L.A. Everett, H. Morsi, D.K. Wu and E.D. Green, Expression pattern of the mouse ortholog of the Pendred’s syndrome gene (Pds) suggests a key role for pendrin in the inner ear, Proc Natl Acad Sci USA 96 (1999), 9727–9732.

[5] L. Lacroix, C. Mian, B. Caillou, M. Talbot, S. Filetti, M. Schlumberger and J.M. Bidart, Na(+)/I(−) symporter and Pendred syndrome gene and protein expressions in human extra-thyroidal tissues, Eur J Endocrinol 144 (2001), 297–302.

[6] J.M. Bidart, L. Lacroix, D. Evin-Brion, B. Caillou, V. Lazar, R. Eyfrdman, D. Bollet, S. Filetti and M. Schlumberger, Expression of Na(+)/I(−) symporter and Pendred syndrome genes in trophoblast cells, J Clin Endocrinol Metab 85 (2000), 4367–4372.

[7] K. Suzuki, I.E. Royaux, L.A. Everett, A. Mori-Aoki, S. Suzuki, K. Nakamura, T. Sakai, R. Katoh, S. Toda, E.D. Green and L.D. Kohn, Expression of PDS/Pds, the Pendred syndrome gene, in endometrium, J Clin Endocrinol Metab 87 (2002), 938.

[8] I.E. Royaux, L.A. Belyantseva, T. Wu, B. Kachar, L.A. Everett, D.C. Marcus and E.D. Green, Localization and functional studies of pendrin in the mouse inner ear provide insight about the etiology of deafness in pendred syndrome, J Assoc Res Otolaryngol 4 (2003), 394–404.

[9] I.E. Royaux, S.M. Wall, L.P. Karniski, L.A. Everett, K. Suzuki, M.A. Knepper and E.D. Green, Pendrin, encoded by the Pendred syndrome gene, resides in the apical region of renal intercalated cells and mediates bicarbonate secretion, Proc Natl Acad Sci USA 98 (2001), 4221–4226.

[10] I.E. Royaux, K. Suzuki, A. Mori, R. Katoh, L.A. Everett, L.D. Kohn and E.D. Green, Pendrin, the protein encoded by the Pendred syndrome gene (PDS), is an apical porter of iodide in the thyroid and is regulated by thyroglobulin in FRTL-5 cells, Endocrinology 141 (2000), 839–845.

[11] P. Kopp, L. Pesce and S.J. Solis, Pendred syndrome and iodide transport in the thyroid, Trends in Endocrinology and Metabolism 19 (2008), 260–268.

[12] H.H. Kacem, A. Rebai, N. Kaffel, S. Masmoudi, M. Abid and H. Ayadi, PDS is a new susceptibility gene to autoimmune thyroid diseases: association and linkage study, J Clin Endocrinol Metab 88 (2003), 2274–2280.

[13] A. Yoshida, I. Hisatome, S. Taniguchi, Y. Shirayoshi, Y. Yamamoto, J. Mika, T. Ohkura, T. Akama, O. Igawa, C. Shigemasa, K. Kamijo, S. Ikuaya, P. Catregli and K. Suzuki, Pendrin is a novel autoantigen recognized by patients with autoimmune thyroid diseases, J Clin Endocrinol Metab 94 (2008), 442-8.

[14] Y. Nakagami, S. Favoreto, Jr., G. Zhen, S.W. Park, L.T. Nguyenvu, D.A. Kuperman, G.M. Dolganov, X. Huang, H.A. Boushey, P.C. Avila and D.J. Erle, The epithelial anion transporter pendrin is induced by allergy and rhinovirus infection, regulates airway surface liquid, and increases airway reactivity and inflammation in an asthma model, J Immunol 181 (2008), 2203–2210.

[15] I. Nakao, S. Kanaji, S. Ohita, H. Matsushita, K. Arima, N. Yuyama, M. Yamaya, K. Nakayama, H. Kubo, M. Watanabe, H. Sagara, K. Sugiyma, H. Tanaka, S. Toda, H. Hayashi, H. Inoue, T. Hoshino, A. Shiraki, M. Inoue, K. Suzuki, H. Aizawa, S. Okinami, H. Nagai, M. Hasegawa, T. Fukuda, E.D. Green and K. Izuhara, Identification of pendrin as a common mediator for mucus production in bronchial asthma and chronic obstructive pulmonary disease, J Immunol 180 (2008), 6252–6269.

[16] E. Di Valentin, C. Crabay, N. Garbacci, B. Hennuy, M. Guideres, A. Noël, J.M. Foidart, J. Grooten, A. Colige, J. Piette and D. Cataldo, New asthma biomarkers: lessons from murine models of acute and chronic asthma, Am J Physiol Lung Cell Mol Physiol 296 (2009), 185–197.
H. Hadj-Kacem et al. / SLC26A4 variations among Graves’ hyper-functioning thyroid gland

[17] D.A. Kuperman, C.C. Lewis, P.G. Wooldruff, M.W. Rodriguez, Y.H. Yang, G.M. Dolgani, J.V. Fahy and D.J. Erle, Dissecting asthma using focused transgenic modeling and functional genomics, J Allergy Clin Immunol 116 (2005), 305–311.

[18] G. Zhen, S.W. Park, L.T. Nguyenv, M.W. Rodriguez, R. Barbeau, A.C. Paquet and D.J. Erle, IL-13 and epidural growth factor receptor have critical but distinct roles in epithelial cell mucin production, Am J Respir Cell Mol Biol 36 (2007), 244–253.

[19] A.C. Madoe, A. Manichaikul, S.P. Pryor and A.J. Griffith, Do mutations of the Pendred syndrome gene, SLC26A4, confer resistance to asthma and hypertension? J Med Genet 46 (2009), 405–406.

[20] D.B. Mount and M.F. Romero, The SLC26 gene family of multifunctional union exchangers. Pflugers Arch 447 (2004), 710–721.

[21] A. Yoshida, S. Taniguchi, I. Hisatome, I.E. Royaux, E.D. Green, I.D. Kohn and K. Suzuki, Pendrin is an iodide-specific apical porter responsible for iodide efflux from thyroid cells, Journal of Clinical Endocrinology and Metabolism 87 (2002), 3356–3361.

[22] A. Yoshida, I. Hisatome, S. Taniguchi, N. Sasaki, Y. Yamamoto, J. Miake, H. Fukui, H. Shimizu, T. Okamura and T. Okubu, Mechanism of iodide/chloride exchange by pendrin, Endocrinology 145 (2004), 4301–4308.

[23] M.P. Gillam, A.R. Sidhaye, E.J. Lee, J. Rutishauer, C.W. Stephan and P. Kopp, Functional characterization of pendrin in a polarized cell system. Evidence for pendrin-mediated apical iodide efflux, Journal of Biological Chemistry 279 (2004), 13004–13010.

[24] G.R. Fraser, Association of congenital deafness with goitre (Pendred’s syndrome) a study of 207 families, Annals of Human Genetics 28 (1965), 201–249.

[25] H.J. Park, S. Shaukat, X.Z. Liu, S.H. Hahn, S. Naz, M. Ghosh, H.N. Kim, S.K. Moon, S. Abe, K. Tukamoto, S. Riazuddin, M. Kabra, R. Erdenetungalag, J. Radnaabazar, S. Khan, A. Pandya, S.I. Usami, W.E. Nance, E.R. Wilcox, S. Riazuddin and A.J. Griffith, Origins and frequencies of SLC26A4 (PDS) mutations in east and south Asians: global implications for the epidemiology of deafness, J Med Genet 40 (2003), 242–248.

[26] T. Yang, H. Vidarsson, S. Rodrigo-Blomqvist, S.S. Rosen gren, S. Enerback and R.J. Smith, Transcriptional control of SLC26A4 is involved in Pendred syndrome and nonsyndromic enlargement of vestibular aqueduct (DFN6B), American Journal of Human Genetics 80 (2007), 1055–1063.

[27] L. Fugazzola, N. Cerutti, D. Mannavola, G. Vannucchi and P. Beck-Peccoz, The role of pendrin in iodide regulation, Experimental and Clinical Endocrinology and Diabetes 109 (2001), 18–22.

[28] R. Grimaldi, P. Capuano, N. Miranda, C. Wagner and G. Capasso, Pendrin: physiology, molecular biology and clinical importance, Giornale Italiano di Neurologia 24 (2007), 288–294.

[29] P. Illum, H.W. Kjaer, J. Hvildberg-Hansen and G. Sondergaard, Fifteen cases of Pendred’s syndrome. Congenital deafness and sporadic goiter, Archives of Otolaryngology 96 (1972), 297–304.

[30] K. Banghova, E. Al Taji, O. Cinek, D. Novotna, R. Pourova, J. Zapletalova, O. Hinkova and J. Lebl, Pendred syndrome among patients with congenital hypothyroidism detected by neonatal screening: identification of two novel PDS/SLC26A4 mutations, Eur J Pediatr 167 (2008), 777–783.

[31] K. Banghova, O. Cinek, E. Al Taji, J. Zapletalova, R. Vidur ra and J. Lebl, Thyroidectomy in a patient with multinodular dysmorphogenetic goitre—a case of Pendred syndrome confirmed by mutations in the PDS/SLC26A4 gene, J Pediatr Endocrinol Metab 21 (2008), 1179–1184.

[32] N. Pfarr, G. Borck, A. Turk, U. Napiotnek, A. Keilmann, W. Müller-Forell, P. Kopp and J. Pohlenz, Goitrous congenital hypothyroidism and hearing impairment associated with mutations in the TPO and SLC26A4/PDS genes, J Clin Endocrinol Metab 91 (2006), 2678–2681.

[33] S. Dossema, S. Rodighiero, V. Vezzoli, C. Nofziger, E. Salvioni, M. Boccazzi, E. Grabmayer, G. Botti, G. Mey er, L. Fugazzola, P. Beck-Peccoz and P. Paulmichl, Functional characterization of wild-type and mutated pendrin (SLC26A4), the anion transporter involved in Pendred syndrome, J Mol Endocrinol 43 (2009), 93–103.

[34] H. Blons, D. Feldmann, V. Duval, O. Messaz, F. Denoyelle, N. Loundon, A. Sergout-Allaoui, M. Houang, F. Duriez, D. Lacombe, B. Delobel, J. Leman, H. Catsor, J. Hourmel, V. Drouin-Garraud, M.F. Obstoy, A. Toutain, S. Oden, J.E. Toublanc, R. Couderc, C. Petit, E.N. Garabédian and S. Marlin, Screening of SLC26A4 (PDS) gene in Pendred’s syndrome: a large spectrum of mutations in France and phenotypic heterogeneity, Clin Genet 66 (2004), 333–340.

[35] S. Albert, H. Blons, L. Jonard, D. Feldmann, P. Chauvin, N. Loundon, A. Sergout-Allaoui, M. Houang, J. Aronnard, S. Schmerber, B. Delobel, J. Leman, H. Hourmel, H. Catsor, H. Dolfuss, M.M. Eliot, A. David, C. Calais, V. Drouin-Garraud, M.F. Obstoy, P. Tran Ba Huy, D. Lacombe, F. Duriez, C. Francanet, P. Bitoun, C. Petit, E.N. Garabédian, R. Couderc, S. Marlin and F. Denoyelle, SLC26A4 gene is frequently involved in nonsyndromic hearing impairment with enlarged vestibular aqueduct in Caucasian populations, Eur J Hum Genet 14 (2006), 777–779.

[36] P. Dai, A.K. Stewart, F. Chebib, A. Hsu, J. Rozenfeld, D. Vaidya, R. Coffey, B. Coyle, R. Trembath, C. San Lazaro, Y. Yuan, M. Kenna, D.T. Miller, Y. Shen, W. Yang, I. Zelikovic, J. Zapletalova, O. Hnikova and J. Lebl, Thyroidectomy in a patient with multinodular dysmorphogenetic goitre–a case of Pendred syndrome confirmed by mutations in the PDS/SLC26A4 gene, J Pediatr Endocrinol Metab 21 (2008), 1179–1184.

[37] A. Pera, S. Dossema, S. Rodighiero, M. Gandia, G. Botta, G. Meyer, F. Moreno, C. Nofziger, C. Hernandez-Chico and P. Paulmichl, Functional assessment of allelic variants in the SLC26A4 gene involved in Pendred syndrome and nonsyndromic EVA, Proc Natl Acad Sci USA 105 (2008), 18608–18613.

[38] B. Vaidya, R. Coffey, B. Coyle, R. Trembath, C. San Lazaro, W. Reardon and P. Kendall-Taylor, Concurrence of Pendred syndrome, autoimmune thyroiditis, and simple goiter in one family, J Clin Endocrinol Metab 94 (1999), 2736–2738.

[39] L.M. Ibrahim, D.O. McDonald, C.J. Owen, P. Kendall-Taylor and S.H.S. Pearce, Graves’ Hyperthyroidism in a Patient with Pendred’s Dysmorphogenesis, Hot thyroidology 13 (2009), 1–8.