Non-pheochromocytoma (PCC)/paraganglioma (PGL) tumors in patients with succinate dehydrogenase-related PCC–PGL syndromes: a clinicopathological and molecular analysis

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Abstract

Objective: Although the succinate dehydrogenase (SDH)-related tumor spectrum has been recently expanded, there are only rare reports of non-pheochromocytoma/paraganglioma tumors in *SDHx*-mutated patients. Therefore, questions still remain unresolved concerning the aforementioned tumors with regard to their pathogenesis, clinicopathological phenotype, and even causal relatedness to *SDHx* mutations. Absence of SDHB expression in tumors derived from tissues susceptible to SDH deficiency is not fully elucidated.

Design and methods: Three unrelated *SDHD* patients, two with pituitary adenoma (PA) and one with papillary thyroid carcinoma (PTC), and three *SDHB* patients affected by renal cell carcinomas (RCCs) were identified from four European centers. SDHA/SDHB immunohistochemistry (IHC), *SDHx* mutation analysis, and loss of heterozygosity analysis of the involved *SDHx* gene were performed on all tumors. A cohort of 348 tumors of unknown *SDHx* mutational status, including renal tumors, PTCs, PAs, neuroblastic tumors, seminomas, and adenomatoid tumors, was investigated by SDHB IHC.

Results: Of the six index patients, all RCCs and one PA displayed SDHB immunonegativity in contrast to the other PA and PTC. All immunonegative tumors demonstrated loss of the WT allele, indicating bi-allelic inactivation of the germline mutated gene. Of 348 tumors, one clear cell RCC exhibited partial loss of SDHB expression.

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Conclusions: These findings strengthen the etiological association of *SDHx* genes with pituitary neoplasia and provide evidence against a link between PTC and *SDHx* mutations. Somatic deletions seem to constitute the second hit in *SDHB*-related renal neoplasia, while *SDHx* alterations do not appear to be primary drivers in sporadic tumorigenesis from tissues affected by SDH deficiency.

Introduction

Familial paraganglioma (PGL) syndromes, caused by *SDHx* (*A*, *B*, *C*, *D*, and -*AF2*) mutations, are rare syndromes inherited as autosomal dominant traits with *SDHD* and *SDHAF2* mutations being associated with a striking parent of origin phenotypic expression (1). The *SDHA/B/C/D* genes encode for the four subunits of succinate dehydrogenase (SDH) or mitochondrial complex II, while the *SDHAF2* gene encodes SDH complex assembly factor 2 (SDHAF2) that ensures flavination of SDHA, which is essential for the functional and structural integrity of the SDH complex (2). Mitochondrial complex II, bound to the inner mitochondrial membrane, is the only enzyme participating both in the tricarboxylic acid/Krebs cycle and oxidative phosphorylation and thereby links deregulation of these cellular functions to tumorigenesis (2).

Although familial PGL syndromes were initially thought to predispose only for pheochromocytoma (PCC) and PGL, other tumor types such as gastrointestinal stromal tumors (GISTs) (2, 3), renal cell carcinomas (RCCs) (4), and pituitary adenomas (PAs) (5, 6) have expanded the *SDHx*-associated tumor spectrum. Several other neoplasms have been reported in *SDHx* mutation carriers including papillary thyroid carcinoma (PTC), medullary thyroid carcinoma, pancreatic neuroendocrine tumor, adrenal cortical adenoma, neuroblastoma (NBL), ganglioneuroma (GN), adenomatoid tumor of the adrenal gland, melanoma, lung cancer, breast carcinoma, oesophageal cancer, rectal and ovarian carcinomas, uterine adenocarcinoma, uterine leiomyoma, testicular seminoma, bladder cancer, meningioma, oligodendroglioma, cecal polyps, and hematolymphoid malignancies (7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19).

However, whether these tumors coincidentally occurred in these patients or are causally related to the *SDHx* germline mutation is largely unknown. Biallelic inactivation of *SDHx* genes has only been reported in six RCC cases (8, 16, 20, 21), two PAs (5, 6), one NBL (14), and one testicular seminoma (15) but was not identified in a PA (7), PTC (16), or small-cell lung carcinoma (8). Despite the fact that *SDHx* inactivation may contribute to these particular phenotypes, the significance of this contribution remains unclear given the relative lack of studies displaying an increased lifetime risk for these tumors arising in the context of an SDH-deficient state (22).

With regard to *SDHB*-related RCCs, two independent groups have described specific morphological features (11, 23), suggesting a genotype–phenotype association similar to what has been described for other hereditary forms of *VHL*-, *MET*-, *FLCN*-, *FH*-, *MITF*-, *TSC1/2*-, and *PTEN*-related renal neoplasia (24). By contrast, previous reports of a diverse histopathological spectrum, encompassing oncocytoma (14, 25), clear cell RCC (26, 27), eosinophilic chromophobe RCC (27), papillary RCC (type II) (28, 29, 30), poorly differentiated tumor with a papillary architecture and sarcomatoid areas (11, 31), and angiomyolipoma (32), indicated morphological heterogeneity in *SDHB*-related neoplasia.

In an effort i) to determine whether the occurrence of two PAs was related to *SDHD* mutations, ii) to elucidate PTC as a component of the *SDHx*-related tumor spectrum, and iii) to search for potential genotype–phenotype correlations and clarify the nature of the second hit in *SDHB*-associated renal neoplasia, seven tumors from six *SDHB*- or *SDHD*-mutated patients were meticulously investigated. Moreover, we explored loss of the SDH complex by SDHB immunohistochemistry (IHC) in a large series of 348 tumors of unknown *SDHx* mutational status, including renal tumors, PAs, PTCs, neuroblastic tumors, seminomas, and adenomatoid tumors.

Subjects and methods

Tissue samples

For the case series, archival specimens of tumor and normal formalin-fixed paraffin-embedded (FFPE) tissues

were provided by four hospitals from The Netherlands (Erasmus MC, University Medical Center (EMC) and Leiden University Medical Center (LUMC)), Norway (Oslo University Hospital), and Germany (University Medical Center of the Johannes Gutenberg University Mainz). All available cases ($n=6$) were ascertained from the histopathology archives at each center. Clinical and genetic characteristics of these patients are detailed in Table 1. Informed consent was obtained for genetic analysis and access to the clinical data in accordance with institutional guidelines.

The second series included 348 tumors of unknown *SDHx* mutational status diagnosed at Erasmus MC (130 renal tumors (80 clear cell RCCs, 19 papillary RCCs, 15 chromophobe RCCs, and 16 oncocytomas), 60 PTCs, 47 peripheral neuroblastic tumors (38 primary tumors and nine metastases), and four composite PCC/GN, 50 seminomas, ten adenomatoid tumors, and 41 PAs (27 GH-, eight PRL-, one FSH-, and one ACTH-secreting and/or positive on IHC as well as four non-functional ones)) and at the Department of Pathology, University Health Network (six PAs (acidophil stem cell adenomas)). These were assessed anonymously according to the Proper Secondary Use of Human Tissue code established by the Dutch Federation of Medical Scientific Societies (http://www.federa.org). The Medical Ethical Committee of the Erasmus MC approved the study.

SDHA/SDHB IHC

All non-PCC/PGL tumors from three *SDHB*- and three *SDHD*-mutated patients were analyzed with SDHA and SDHB IHC. Stainings were performed on 4–5 μm sections of FFPE blocks as described previously (9, 33). The following primary antibodies against SDHA and SDHB were used: mouse monoclonal 2E3GC12FB2AE2 (Mitosciences, Abcam; 1:500) and rabbit polyclonal HPA002868 (Sigma–Aldrich Corp.; 1:400) respectively.

All 348 tumors from the second series were initially analyzed with SDHB IHC (and SDHA IHC in the eventuality of SDHB immunonegativity). If the internal control (granular staining in endothelial cells) was

Table 1 Clinical and molecular characteristics of non-PCC/PGL tumors in *SDHB/SDHD*-mutated patients. PCC and/or PGLs were not subjected to genetic analyses but to SDHB/SDHA IHC displaying SDHB immunonegativity and SDHA immunopositivity.

Case no.	Age[a]/sex	Germline *SDHx* mutation	Tumors observed (age at detection)	SDHB IHC	SDHA IHC	Second hit[b] (LOH)	Status at last follow-up/age
1	60/M	*SDHD* c.274G>T (p.Asp92Tyr)	HN PGLs PA (60 years) PCC (62 years)	Neg	Pos	Pos	AWED/68
2	56/F	*SDHD* c.274G>T (p.Asp92Tyr)	HN PGLs (56 years) PA (56 years)	Pos	Pos	Neg	AWED/68
3	25/F	*SDHD* c.14G>A (p.Trp5X)	CBT (17 years) GJT (17 years) CBT (25 years) PTC (25 years) PCCs (26 years) ea PGL (26 years) ea PGL (25 years)	Pos	Pos	Neg[c]	NA/27
4[d]	25/M	*SDHB* c.3G>A (p.Met1Ile)	RCC1 (L) (25 years) RCC2 (L) (25 years) RCC (R) (31 years)	Neg / Neg	Pos / Pos	Pos / Pos	AWED/31
5	23/M	*SDHB* c.3G>A (p.Met1Ile)	RCC (23 years)	Neg	Pos	Pos	AWED/28
6	36/M	*SDHB* Exon 3 del	GJT (30 years) CBT (34 years) RCC (36 years)	Neg	Pos	Pos	AWD/47

AWD, alive with disease; AWED, alive without evidence of disease; CBT, carotid body tumor; ea PGL, extra-adrenal paraganglioma; GJT, glomus jugulare tumor; HN PGL, head and neck paraganglioma; IHC, immunohistochemistry; L, left; NA, not available; PA, pituitary adenoma; PCC, pheochromocytoma; PTC, papillary thyroid carcinoma; R, right; RCC, renal cell carcinoma.
[a]Years at diagnosis of non-PCC/PGL tumor.
[b]None of the evaluated tumors displayed a somatic mutation as a second hit.
[c]Sequencing chromatograms of PTC DNA displayed i) both the mutated and the WT allele at a ratio 50:50, ii) no somatic mutation as a second hit, and iii) retention for a microsatellite marker telomeric to *SDHD* with LOH analysis. It should be noted that the patient was homozygous (not informative) for two markers centromeric to *SDHD* (LOH electropherograms not shown).
[d]Non-PCC/PGL tumors of this sibling were tested in Norway.

European Journal of Endocrinology

positive, slides were considered suitable. From SDHB immunonegative/SDHA immunopositive tumors, i) the entire *SDHB*, *SDHC*, *SDHD*, and *SDHAF2* coding sequences were assessed for mutations and large intragenic deletions at the germline and somatic level by direct sequencing and multiplex ligation-dependent probe amplification (MLPA) assay with a commercially available kit (SALSA MLPA P226-B2; MRC Holland, Amsterdam, The Netherlands) and ii) loss of heterozygosity (LOH) analysis was performed for polymorphic microsatellite markers flanking the *SDHB*, *SDHC*, *SDHD*, and *SDHAF2* genes.

Mutation screening

DNA isolation from tumors was carried out using standard procedures following manual microdissection (to assess somatic mutations as a potential second hit). All tumor samples were estimated to contain at least 80% neoplastic cells. The full coding sequence, including intron–exon boundaries, of the *SDHD* and *SDHB* genes was screened by direct sequencing in forward and reverse orientation (experimental details available on request).

LOH analysis

LOH analysis was performed for polymorphic microsatellite markers flanking either the *SDHB* or the *SDHD* gene. For this, PCR was performed with fluorescence-labeled primers (Invitrogen; primer sequences are available on request) for 35 cycles with an annealing temperature of 60 °C and amplified products analyzed, along with LIZ 500 size standard (Applied Biosystems), using capillary electrophoresis on an ABI 3130-XL genetic analyzer (Applied Biosystems). Data were analyzed using GeneMarker Software (Soft-Genetics LLC, State College, PA, USA).

Results

Case series

Case 1 ▶ A 60-year-old male with a history of multiple head and neck PGLs (HN PGLs) and a previously diagnosed germline c.274G>T (p.Asp92Tyr) *SDHD* gene mutation presented with a PRL-producing macroadenoma causing bitemporal hemianopsia and was treated with dopamine agonists, subsequently leading to PA shrinkage (10). Two years later, the patient developed meningitis and liquorrhoea, for which he was treated with antibiotics and underwent a transsphenoidal partial resection of the macroadenoma along with restoration of the sella turcica.

The same year, a right-sided PCC was laparoscopically resected. Postoperatively, urinary catecholamine excretion normalized. On the preoperative magnetic resonance imaging (MRI), an additional iodine-123-meta-iodobenzylguanidine (MIBG)-negative 7 mm nodule was visualized in the left adrenal gland, suspicious of an adenoma, for which a wait and scan strategy has been followed. Endocrine tests revealed no hormone production by this nodule. Owing to increasing prolactin levels postoperatively and residual tumor on the pituitary MRI, cabergoline therapy was reintroduced leading eventually to normal prolactin levels. Family history was positive for HN PGL, but negative for pituitary tumors. The patient is alive 6 years after the resection of the macroadenoma and PCC and is receiving hormone replacement for hypopituitarism with levothyroxine, hydrocortisone, androgel, and minrin.

Case 2 ▶ A 56-year-old female with a history of type 2 diabetes mellitus, hypertension, and a nontoxic nodular goiter was referred due to a right-sided vocal cord paralysis on the basis of a vagal PGL (10). On further evaluation, bilateral carotid body tumors were revealed. Screening MRI along with endocrine tests demonstrated a GH-producing pituitary macroadenoma, which was partially removed by transsphenoidal resection followed by treatment with somatostatin analogs. The diagnosis was confirmed on histopathological grounds (Fig. 1). The patient was subsequently shown to harbor a heterozygous germline mutation c.274G>T (p.Asp92Tyr) in the *SDHD* gene. Family history was positive for HN PGL (father, two sisters) and gastric GIST (sister), while negative for pituitary tumors. The patient is alive with intact pituitary function 12 years after surgery.

Case 3 ▶ A previously reported 25-year-old female with a history of HN PGLs was operated on for a left carotid body tumor and PTC (T1N0 unicentric tumor in the right lobe; Fig. 2) (34, 35). One year later, she presented with bilateral PCCs and an intra-abdominal extra-adrenal (ea) PGL and was subsequently shown to harbor a heterozygous germline *SDHD* mutation c.14G>A (p.Trp5X). Although there was suspicion based on imaging studies for metastatic foci affecting the lungs and a peri-pancreatic lymph node, no biopsy was performed in order to confirm and specify the origin of metastases. The patient was lost to follow-up 12 months postoperatively. No other family members were evaluated for *SDHD* mutations or screened for relevant tumors.

Cases 4 and 5 ▸ A 25-year-old male (case no. 4) presented with periods of headache, throbbing chest pain, sweating, dizziness, and palpitations associated with episodic hypertension. On laboratory investigation, the nor-adrenaline levels in blood and urine appeared almost 20 times higher than the upper normal limit. Computed tomography (CT) scan of the abdomen revealed a para-aortic mass as well as two large solid tumors in the left kidney with relative homogeneous uptake. MRI scanning of the brain, spine, neck, and thorax showed no abnormalities. The patient underwent a left-sided nephrectomy and resection of the retroperitoneal mass and was subsequently diagnosed with two RCCs measuring 9 cm (RCC1) and 2.8 cm (RCC2) in maximum
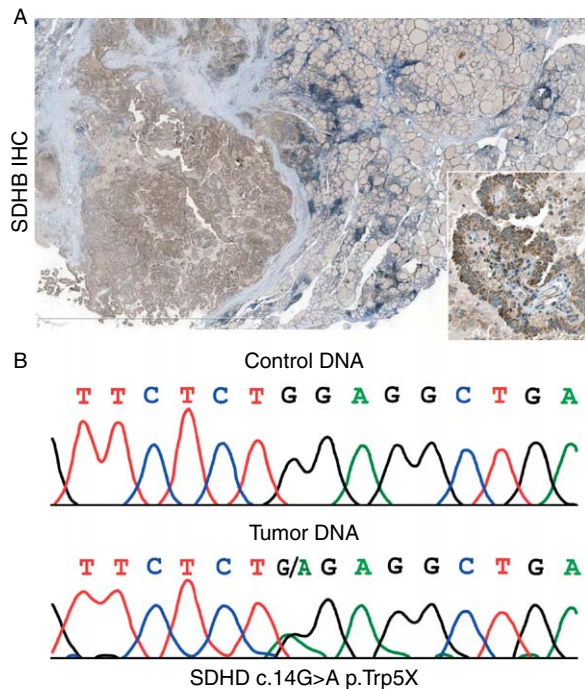

diameter and an intra-abdominal ea PGL. Histopathologically, the RCCs were originally classified as combined oncocytoma/chromophobe RCC and unclassified RCC respectively. Twenty-four-hour urinary excretion of catecholamines and total metanephrines were postoperatively normalized. *SDHB* sequence analysis revealed a heterozygous germline start codon mutation c.3G>A (p.Met1Ile). An MIBG scan and CT scan performed 6 months postoperatively showed no evidence of recurrent or metastatic disease. However, 6 years postoperatively, a 1.3 cm tumor in the right kidney close to the hilus was treated by open radiofrequency ablation. Identical mutations were identified in both his father and two brothers. One of the latter underwent biochemical and radiological screening for catecholamine-secreting PGLs. Although these investigations were negative for PGLs, the younger sibling (case no. 5) suffered from a 2.5 cm renal tumor requiring a right-sided kidney resection at age 23 years. On histopathological grounds, the renal tumor was originally classified as clear cell RCC (Fuhrman grade 2).

Case 6 ▸ A 47-year-old male was originally diagnosed with a left jugulotympanic PGL at the age of 30 years after a period of unilateral hearing loss and tinnitus. The tumor was surgically resected without major complications. Four years later, a carotid body PGL was detected and treated
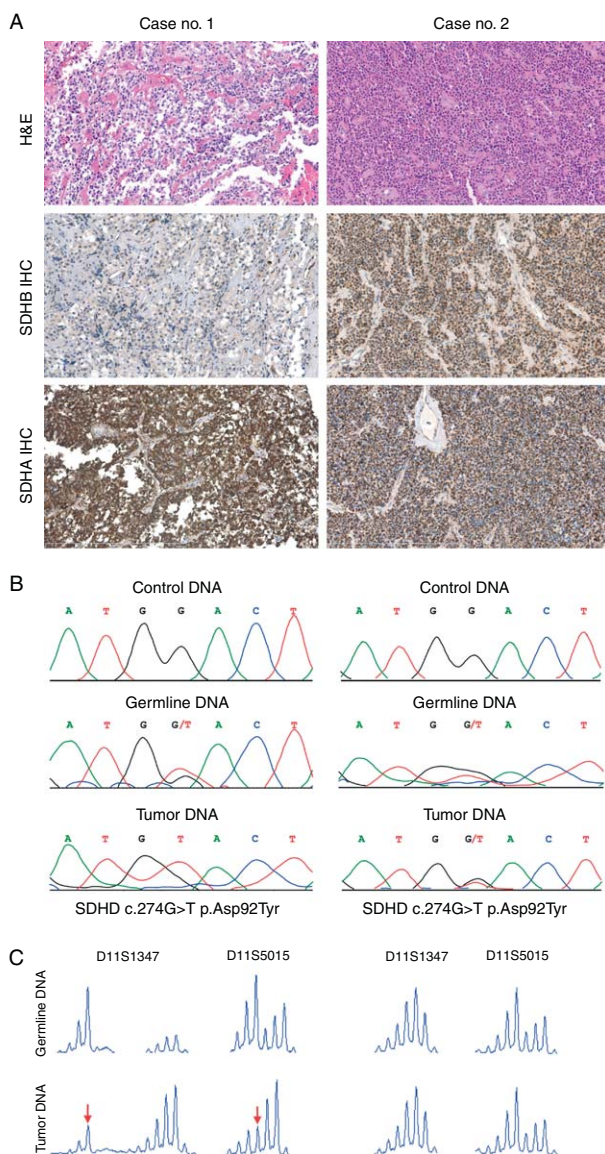
Figure 1

(A) H&E staining and SDHB/SDHA IHC in two pituitary adenomas arising in two unrelated patients carrying the *SDHD* c.274G>T (p.Asp92Tyr) mutation: case no. 1 showed loss of SDHB expression in the neoplastic cells with normal (endothelial) cells serving as positive internal controls, while case no. 2 retained SDHB labeling; on reticulin stain, the latter revealed breakdown of the reticulin fiber network, thereby excluding the possibility of a hyperplastic SDHB[pos] lesion (image not shown). Both tumors showed strong positive staining for SDHA. (B) Sequencing chromatograms of tumor DNA and healthy germline tissue in case nos 1–2: mutational analysis revealed the germline *SDHD* c.274G>T (p.Asp92Tyr) mutation in both the pituitary adenomas and the corresponding normal tissues; only case no. 1 displayed relative loss of the WT *SDHD* allele. (C) Loss of heterozygosity (LOH) electropherograms of case nos 1–2: LOH in the pituitary adenoma (case no. 1) was confirmed using polymorphic microsatellite markers flanking the *SDHD* locus. The red arrows indicate the allele with relative loss. LOH analysis of the other pituitary adenoma (case no. 2) exhibited retention of heterozygosity.

A

SDHB IHC

B

Control DNA

T T C T C T G G A G G C T G A

Tumor DNA

T T C T C T G/A G A G G C T G A

SDHD c.14G>A p.Trp5X

Figure 2

(A) SDHB IHC in a papillary thyroid carcinoma arising in an *SDHD*-mutated individual (case no. 3). At a higher magnification (inset), there is strong granular cytoplasmic staining for SDHB. (B) Sequencing chromatograms of tumor DNA revealed the germline *SDHD* c.14G > A (p.Trp5X) mutation and displayed 50:50 ratio of WT vs mutated allele, indicating retention of heterozygosity. Heterozygosity was retained for a microsatellite marker telomeric to *SDHD*, but the patient was homozygous (not informative) for two markers on the centromeric side (LOH electropherograms not shown).

with radiotherapy. At the age of 36 years, the patient was diagnosed with a renal tumor measuring 13 cm in maximum diameter for which he underwent a left-sided nephrectomy. Histopathologically, the renal tumor was initially diagnosed as eosinophilic chromophobe RCC, while on revision as eosinophilic clear cell RCC (Fuhrman grade 3). Several times hereafter, he suffered from intra-abdominal RCC recurrences and splenic metastasis necessitating surgical resection. Nine years postoperatively, liver metastases were detected on imaging; hence, the patient was treated with radiofrequency ablation and sunitinib. Although being unresponsive to the latter, he is currently alive with disease 11 years postoperatively. On genetic analysis, the patient was subsequently shown to harbor a heterozygous germline *SDHB* mutation (exon 3 deletion). Family history was negative for HN PGL. Results

of the SDHA/SDHB IHC, mutation screening, and LOH analysis of non-PCC/PGL tumors (case nos 1–6) are detailed in Table 1.

Histopathology of the *SDHB*-associated RCCs

The RCCs from case nos 4–6 shared similar morphological features, as illustrated in Fig. 3 and Supplementary Figs 1 and 2, see section on supplementary data given at the end of this article. All RCCs displayed characteristic eosinophilic appearance and pale eosinophilic and/or bubbly intracytoplasmic inclusions, as described previously (11, 23). In particular, the neoplastic cells were polygonal with eosinophilic granular cytoplasm and centrally placed nuclei, which were either relatively uniform with inconspicuous nucleoli (RCC1 case nos 4 and 5) or pleomorphic with prominent nucleoli (RCC2 case nos 4 and 6). Tumor cells were arranged mainly in nested and solid growth patterns with occasional tubular formations. In addition, case no. 6 displayed a focal papillary growth pattern (Supplementary Fig. 2). All tumors were well-circumscribed exhibiting areas of cystic change, which contained eosinophilic material (Fig. 3). RCC1 case nos 4 and 6 showed necrotic areas. All RCCs demonstrated SDHB immunonegativity and SDHA immunoreactivity, as highlighted in Fig. 3 and Supplementary Figs 1 and 2.

SDHx alterations in unselected tumors of unknown *SDHx* mutational status

Of the 348 genetically uncharacterized tumors, one clear cell RCC was partly immunonegative for SDHB (1/130 renal tumors, 0.8%; Table 2). Histopathologically, the tumor measuring 9.6 cm in maximum diameter comprised low-grade (Fuhrman grade 1) and high-grade areas (up to Fuhrman grade 4) along with sarcomatoid differentiation and extensive areas of necrosis. Although distinctive cytoplasmic inclusions could not be detected, focal vacuolation was present only in high-grade areas. The latter were found to be SDHB^{neg}/SDHA^{pos} compared with the SDHB^{pos}/SDHA^{pos} low-grade tumor component (Fig. 4). The patient developed lung metastases 3 months following surgical resection, for which he was treated with sunitinib. However, he was unresponsive and eventually succumbed to metastatic disease 5 months postoperatively at age 55 years.

Sequencing and MLPA analysis of the SDHB^{neg} tumor component and normal tissue for *SDHB*, *SDHC*, *SDHD*, and *SDHAF2* genes revealed large intragenic *SDHD* and *SDHAF2* deletions only in the tumor. Being consistent
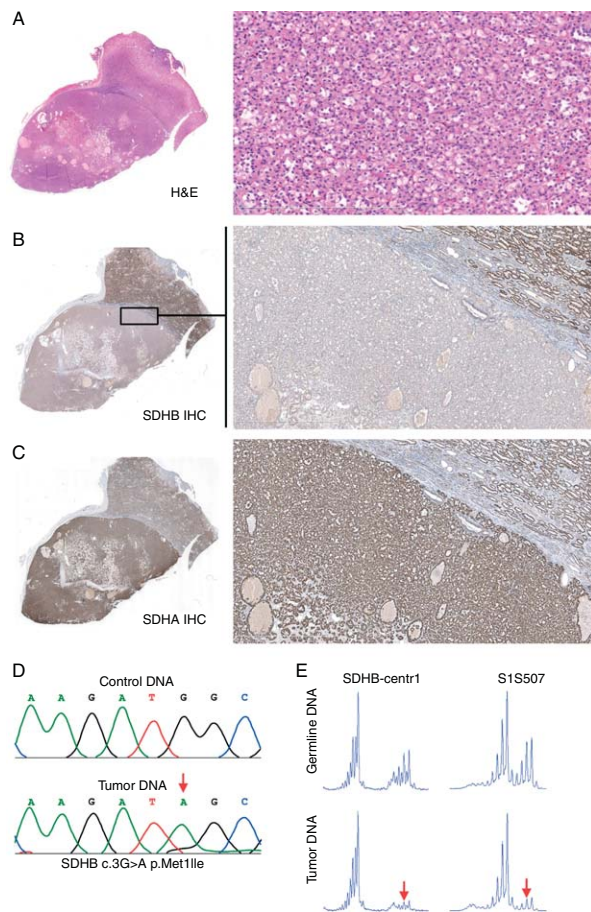
Figure 3

(A, B and C) Histological features (H&E staining) and SDHB/SDHA IHC in the RCC of case no. 5: (A) section of RCC and adjacent non-neoplastic renal parenchyma; the interface with the latter is circumscribed, while there are discrete intratumoral areas of cystic change (left). The neoplastic cells are arranged mainly in a nested growth pattern with tubular formations and cytoplasmic inclusions recognized as well. (B) SDHB IHC displaying immunonegativity in the neoplastic cells as opposed to the non-tumoral kidney. (C) SDHA IHC showing immunopositivity in both neoplastic and non-neoplastic renal compartments. (D and E) Sequencing chromatogram of tumor DNA and loss of heterozygosity (LOH) electropherogram: (D) sequence of *SDHB* exon 1 in the RCC demonstrating a c.3G>A transversion, leading to a premature stop codon, and relative loss of the WT *SDHB* allele. The red arrow indicates the mutation. (E) LOH in the RCC was verified using microsatellites linked to the *SDHB* locus. The red arrows indicate the allele with relative loss.

with the latter, LOH analysis revealed LOH both at the *SDHAF2* locus (Fig. 4) and for a microsatellite marker centromeric to *SDHD*, while the patient was homozygous (not informative) for three markers on the telomeric side (data not shown). No germline *SDHx* mutations or large deletions were detected by direct sequencing or MLPA respectively.

Discussion

Familial PGL syndromes are multiple neoplasia syndromes primarily characterized by the development of PCCs/PGLs. Consistent with the wide expression and the functional role of the *SDHx* genes, it has been suggested that associations with neoplasms other than PCCs/PGLs may exist (36). In this study, we further strengthen the link between pituitary neoplasia and germline *SDHx* mutations and suggest that the occurrence of PTC in *SDHx* mutation carriers might rather be coincidental.

In accordance with the classical 'two-hit hypothesis' of Alfred Knudson (the combination of an inactivating germline mutation as a first hit and somatic loss of function of the WT allele as a second hit being essential for the tumor development) (37), one of the PAs of an *SDHD* patient displayed somatic allelic deletion at the *SDHD* locus resulting in SDHB immunonegativity (Fig. 1). This is consistent with Xekouki *et al*. (6) who observed *SDHD* LOH accompanied by decreased SDH enzymatic activity in one GH-secreting PA and preliminary data concerning another relevant case in the SDH-deficient setting (5) (Supplementary Table 1, see section on supplementary data given at the end of this article). By contrast, the other PA demonstrated retention of *SDHD* heterozygosity, which is in accordance with the positive

Table 2 Immunohistochemical SDHB losses in 348 neoplasms of unknown *SDHx* mutational status.

Tumor type	SDHB immunonegativity
Renal tumors	1/130
Clear cell renal cell carcinoma	1/80
Papillary renal cell carcinoma	0/19
Chromophobe renal cell carcinoma	0/15
Oncocytoma	0/16
Papillary thyroid carcinoma	0/60
Pituitary adenoma	0/47
Neuroblastic tumors	0/47
Composite PCC/GN	0/4
Testicular seminoma	0/50
Adenomatoid tumor	0/10

GN, ganglioneuroma; PCC, pheochromocytoma.
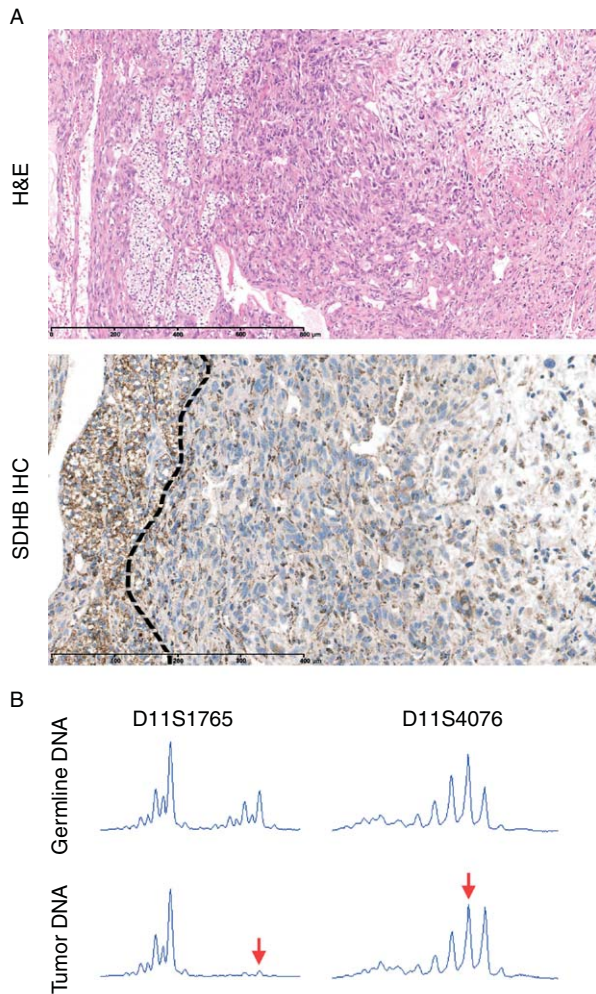
Figure 4

(A) H&E staining and SDHB IHC in a clear cell RCC with sarcomatous dedifferentiation. Both low-grade and high-grade tumor components are illustrated with corresponding SDHB immunopositive/immunonegative areas being distinguished by a dotted line; positive staining of normal (endothelial) cells should not be misinterpreted as positive for the neoplastic cells. (B) LOH in the SDHB immunonegative component was verified using microsatellites linked to the *SDHAF2* locus. The red arrows indicate the allele with relative loss.

SDHB expression (Fig. 1). These findings indicate that this tumor was coincidental and most likely not caused by involvement of the germline *SDHD* mutation. However, *SDHx* gene haploinsufficiency contributing to the tumor formation cannot be ruled out from our analyses. Haploinsufficient effects for the *SDHx* genes have been suggested in: i) bilateral adrenal medullary hyperplasia associated with a germline *SDHB* mutation showing

retention of heterozygosity (38); ii) PCCs without loss of the WT *SDHD* allele arising in *SDHD*-mutated patients (39); and iii) somatic *SDHD* inactivation being accompanied by consistent reduction of transcript levels in various tumors (40, 41). Albeit, in mouse models, no indications were obtained for an *SDHB/SDHD* haploinsufficient contribution to tumorigenesis (42, 43) (J Favier 2013, personal communication).

An extensive literature search revealed ten reported cases of PAs arising in *SDHD/B/C/A*-mutated patients (Supplementary Table 1), with a further 31 PAs co-occurring with PCCs and/or PGLs pointing to a causative association with *SDHx*, *MEN1*, or other yet unidentified predisposing genes (44, 45, 46). *SDHx*-mutated patients appear to have a characteristic clinical phenotype with *PRL*-secreting macroadenomas, and to a lesser extent *GH*-secreting macroadenomas, usually accompanied with a personal history of PCC/PGL, implying that SDH deficiency might promote tumor growth with lactotrophs being more susceptible to this particular deficient state.

Although PTC has been previously suggested as a component of familial PGL syndromes and the risk of thyroid tumor development in *SDHB* mutation carriers has been estimated at 2.5% up to age 70 years (22), a causal role of SDH deficiency in thyroid tumorigenesis has not yet been established. Arguing against such a causal role, our case displayed SDHB immunoreactivity with retention of the WT allele (Fig. 2) being in accordance with a previously reported PTC (16), a rather small number of reported PTC-affected individuals carrying germline *SDHx* mutations and a lack of family PTC history in four of five cases in total (Supplementary Table 2, see section on supplementary data given at the end of this article).

According to prior studies from three large multinational and/or multicenter cohorts (22, 35, 47), examining 110, 116, and 358 *SDHB/SDHD* mutation carriers respectively, only six thyroid tumors were identified: two PTCs (35), one thyroid PGL (47, 48), as well as three thyroid tumors of unknown histopathology (22). Given the high PTC incidence rates (incidence of PTC estimated at 7.3/100 000) (49, 50), it is no surprise that thyroid tumors are relatively frequently encountered as incidental findings in patients who are under active surveillance. Taken together, the occurrence of PTCs in the SDH-deficient state may be either coincidental, reflecting the highly prevalent nature of this particular malignancy, or may be less likely attributable to cross talk of *SDH*- and *PTEN*-related signaling pathways leading to tissue-specific Cowden syndrome (CS)/CS-like tumorigenesis (51, 52).

With regard to *SDHB*-related renal neoplasia, all RCC cases (case nos 4–6) confirm previous histopathological and SDHB immunohistochemical observations (11, 23), highlighting the fact that distinct morphological traits along with SDHB immunonegativity could aid in screening for *SDHB* mutations. In addition, LOH seems to constitute the main mechanism of inactivation of the WT allele in these tumors as observed in *SDHx*-related tumorigenesis (40, 53). Taking into consideration: i) the rarity of *SDHB*-related RCC cases (8, 11, 14, 16, 21, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32, 35, 54); ii) the broad distribution of various germline mutations (missense, nonsense, frameshift, and splice site) and large deletions throughout the *SDHB* gene (Supplementary Fig. 3, see section on supplementary data given at the end of this article); and iii) the fact that mutations within the same codon can generate variable phenotypes (current study, *SDHB* c.3G>A p.Met1Ile; PCC/PGL and/or RCC), previous challenges in establishing genotype–phenotype correlations become conceivable (22).

Interestingly, one clear cell RCC with sarcomatoid dedifferentiation was found to be partly SDHB immuno-negative (1/130, 0.8%; Fig. 4) being in accordance with other *SDHB* mutational or immunohistochemical studies (31, 55, 56). Given that the low-grade tumor component retained SDHB expression, this raises the question as to whether this finding is simply a serendipitous secondary event resulting from genomic instability or has an active role in RCC progression. Mechanisms other than germline *SDHx* mutations, including mutations in as yet unidentified susceptibility gene(s) affecting SDH complex assembly/function, abnormal functional interactions with mitochondrial proteins, and/or epigenetic alterations, could be responsible for loss of protein expression (57, 58). Another plausible explanation is that HIF1a accumulation due to impaired hydroxylation in hypoxic areas (59) might have resulted in downregulated *SDHB* expression either in an auto-regulatory loop (60) or through a putative signaling axis involving HIF1a/microRNA-210/iron-sulfur cluster scaffold protein (ISCU) (61).

By analyzing various tumors from 348 patients of unknown *SDHx* mutational status, all except one were found to be SDHB immunopositive. This is consistent with the notion that mutations of hereditary cancer genes may not be directly involved in tumorigenesis of their sporadic counterparts as reflected in the role of fumarate hydratase (*FH*) in sporadic vs hereditary leiomyomatosis and RCC (62). Although a high percentage of apparently sporadic PCC/PGL cases is causatively linked to germline mutations (1), this is not the case for other tumor types. In particular, only 5–8% of RCCs, 5% of follicular cell-derived well-differentiated thyroid cancers, <5% of PAs, 1–2% of testicular germ cell tumors, and NBLs respectively are familial when compared with 30–35% of PCCs/PGLs (1, 24, 63, 64, 65, 66). With regard to the adenomatoid tumors, there is not only lack of any association with syndromic or genetic conditions but also no example of a typical two-hit mechanisms of TSG inactivation (12).

In conclusion, the current study further strengthens the etiological association of *SDHx* genes with pituitary neoplasia, while it does not support a causative link between PTC- and SDH-deficient state. Additionally, we elucidate clinicopathological and genetic aspects of *SDHB*-related renal neoplasia and report a 0.8% frequency of SDHB immunonegativity in renal tumors, reinforcing the notion that hereditary cancer genes may not always be involved in sporadic tumorigenesis.

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