Rapid-sequence MRI for long-term surveillance for paraganglioma and phaeochromocytoma in patients with succinate dehydrogenase mutations

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Abstract

Background: Patients with SDHx mutations need long-term radiological surveillance for the development of paragangliomas and phaeochromocytomas, but no longitudinal data exist. The aim of the study was to assess the performance of rapid-sequence non-contrast magnetic resonance imaging (MRI) in the long-term monitoring of patients with SDHx mutations.

Methods: Retrospective study between 2005 and 2015 at a University Hospital and regional endocrine genetics referral centre. Clinical and imaging data of 47 patients with SDHx mutations (SDHB (36), SDHC (6) and SDHD (5)) who had surveillance for detection of paragangliomas by rapid-sequence non-contrast MRI (base of skull to pubic symphysis) were collected.

Results: Twelve index cases (nine SDHB, one SDHC and two SDHD) and 35 mutation-positive relatives were monitored for a mean of 6.4 years (range 3.1–10.0 years). Mean age at the end of the study: SDHB 46.9 ± 17.6 years; SDHC 42.3 ± 24.4 years; SDHD 54.9 ± 10.6 years. On excluding imaging at initial diagnosis of index cases, 42 patients underwent 116 rapid-sequence MRI scans: 83 scans were negative and 31 scans were positive for sPGL/HNPGL in 13 patients. Nine patients (three index) were diagnosed with new paragangliomas during surveillance and non-operated tumour size was monitored in nine patients. There were two false-positive scans (1.6%). Scans were repeated every 27 ± 9 months.

Conclusions: Biannual rapid-sequence non-contrast MRI is effective to monitor patients with SDHx mutations for detection of new tumours and monitoring of known tumours.

Introduction

Germ-line mutations of the subunits of the mitochondrial complex II enzyme succinate dehydrogenase (SDHA, SDHB, SDHC, SDHD and SDHAF2), SDHx, are associated with familial paraganglioma (PGL) of the sympathetic chain (sPGL), the parasympathetic chain of the head and neck (HNPGL), and adrenal phaeochromocytoma (1, 2, 3, 4). In general, most phaeochromocytomas secrete catecholamines, whereas sPGLs may be functional or non-secretory, and HNPGLs are usually biochemically silent (5).

SDHx are tumour suppressor genes characterized by loss of heterozygosity in tumour cells due to somatic mutations or loss of expression of the wild-type allele (6, 7). The underlying mechanism of tumorigenesis in
SDHx mutations is still unclear, but non-hypoxic HIF-1alpha and HIF-2alpha activation is a key feature in pathogenesis (‘pseudohypoxia’ hypothesis) (8). In SDHx-related tumorigenesis, there is loss of SDH enzymatic activity and intracellular accumulation of succinate leading to inhibition of prolyl-hydroxylases that usually degrade HIF-1alpha (9, 10, 11). HIF-1alpha is then able to translocate to the nucleus and activate gene expression promoting angiogenesis, cell survival and glycolysis (10). The role of oxygen-sensing pathways in SDHx tumorigenesis is also supported by observations linking living at high altitude and an increase in disease prevalence and phenotypic severity (12, 13).

Patients with SDHx mutations are at a lifelong risk of multifocalf, recurrent and malignant PGLs. Mutations in the different subunits cause specific patterns of disease: individuals with paternally inherited SDHD mutations are more likely to develop HNPGl and multifocal disease and less frequently sPGLs (2, 5, 14, 15); SDHB mutation carriers may develop sPGLs that have a higher malignant potential compared with sporadic or other syndromic PGLs (1, 14); SDHC mutations are rare, with affected individuals developing HNPGl and phaeochromocytoma that have a low risk of malignancy. Penetrance may occur over the life course, but is incomplete and variable: some SDHx members of the same family experience either no tumour development or a benign or asymptomatic course, while others develop devastating and aggressive disease. This underscores the need for appropriate biochemical and imaging screening strategies that may be used in an affected individual over their whole life to detect tumour development, as the primary treatment is resection by an expert surgeon and where better outcomes are found when tumours are detected early (16).

Genetic testing for SDHx mutations has been available for approximately the last decade. Although it is widely accepted that carriers of SDHx mutations should be monitored for the penetrance of the disease, there are no studies reporting the outcome of longitudinal monitoring as highlighted in recently published clinical practice guidelines (17). Therefore, we report our longitudinal 10-year experience of surveillance imaging in a large cohort of SDHx patients attending our dedicated endocrine genetics clinic at a University Hospital using rapid-sequence non-contrast magnetic resonance imaging (MRI) as a non-ionizing imaging modality appropriate for lifelong follow-up to address three key clinical questions: (i) does this MRI technique detect new tumours in patients with SDHx?; (ii) can this MRI technique be used to monitor size and extent of known disease in patients in whom definitive surgical excision has not taken place because of tumour site or patient preference? and (iii) what is an appropriate time interval between imaging studies?

Methods

Patients

The study was approved as a case notes review by our institutional review board (ID number 3861). All patients with pathogenic SDHx mutations (n = 47) attending the dedicated Endocrine Genetics clinic at the Royal Hallamshire Hospital, Sheffield Teaching Hospitals (STH) NHS Foundation Trust, a regional referral centre, from October 2005 to May 2015, were included. A retrospective review of the medical notes, imaging and biochemistry was conducted. All patients were reviewed at each clinic visit by an experienced clinician (JNP). All index cases had either excision of their presenting tumour or other treatment before embarking on surveillance, and the data presented here on imaging are all from the surveillance programme. All mutation-positive relatives had the first surveillance imaging following genetic diagnosis and all their imaging tests are included in the data presented here.

At our institution, genetic testing was performed on patients with phaeochromocytoma aged <50 years or a family history suggesting possible genetically driven disease (such as early cardiac death) or in any patient presenting with sPGL or HNPGl. Genetic testing was performed at the accredited regional genetics laboratory as part of the National Genetics Service of the National Health Service, UK. Carriers of SDHD mutations were offered the screening programme if the mutation was of paternal origin, as it is well-documented that only those inheriting an SDHD mutation from their father exhibit clinical manifestations of the syndrome (3).

All data were discussed at the weekly endocrine multidisciplinary team meeting in the presence of an endocrine radiologist, endocrinologists, endocrine surgeons and chemical pathologists, with the outcome of the studies documented as negative (normal screening), positive (paraganglioma present) or requiring further investigations. As there is no gold standard imaging modality that can be used for long-term surveillance, that is without significant radiation exposure and multiple tests, the outcome of this discussion for each scan was collected and analysed. The outcome of a scan was considered false positive if the lesion was not confirmed to be a paraganglioma at subsequent imaging.
**Surveillance protocol**

At baseline, a detailed clinical assessment was made of all newly referred patients, including a detailed clinical history, clinical examination, together with radiological and biochemical investigations. Thereafter, patients were seen approximately yearly for clinical evaluation and biochemical testing (two 24-h collections of urinary fractionated metanephrines measured by high-performance liquid chromatography from 2005 to 2010 or free plasma metanephrines measured by liquid chromatography-tandem mass spectrometry, since 2010) with radiological evaluation every 2 years. For those with disease detected or lesions that require further characterization, further imaging evaluation and clinical assessments were made on an individualized basis.

**Imaging**

MR images were acquired from skull base to the pubic symphysis, including all sympathetic and parasympathetic ganglia, on a 1.5T Siemens Avanto scanner (Siemens AG Munich) and subsequently reviewed by a single expert endocrine radiologist (MB). The imaging protocol is based on three rapid, unenhanced, non-high-definition sequences (Transverse T1 spin echo in/out phase, Transverse and Coronal T2 Haste). The combination of both T1- and T2-weighted images in two planes gives a survey from skull base to pelvis. Dedicated neck and phased array body coils were used. Parameters for neck imaging: T2 5 mm thickness with 1 mm slice gap TR 3650 ms TE 99 ms matrix size 320 × 70, T1 5 mm thickness with 1 mm slice gap TR 611 ms TE 12 ms matrix size 320 × 70. Parameters for chest, abdomen and pelvis imaging: breath hold sequences T2 Haste 7 mm with 1 mm slice gap TR 1100 ms TE 92 ms matrix size 256 × 80, T1 gradient echo 8 mm thickness with 1 mm slice gap TR 249 ms TE 2.29 ms (out of phase) 4.76 ms (in phase). Each sequence takes usually 2–3 min and the average-sized patient requires this to be done in three blocks. There is no requirement for intravenous contrast in the surveillance scans and the total duration of imaging is 25–30 min. Paragangliomas and phaeochromocytomas have high signal on T2-weighted images. The same protocol was used for all patients regardless of causative mutation.

**Statistical analysis**

Statistical analysis was performed using one-way ANOVA (GraphPad prism 6.0). Results were reported as mean values ± one standard deviation. A P value of less than 0.05 was considered significant.

**Results**

**Patients**

Forty-seven patients with SDHx mutations were included: 36 patients with an SDHB mutation, six with an SDHC mutation and five with an SDHD mutation. Out of 47 patients, 12 were index cases (nine SDHB, one SDHC and two SDHD); the remaining 35 patients were gene-positive relatives. Two patients died during the study, one from complications of metastatic sPGL and one from an unrelated cause. At the end of screening, mean age ± s.d. for SDHB, SDHC and SDHD patients was 46.9 ± 17.6, 42.3 ± 24.4 and 54.9 ± 10.6 years, respectively. The mean age at first tumour for SDHB, SDHC and SDHD patients was 36.1 (15–70), 48.5 (37–60) and 33.3 (22–56) years, respectively. The mean duration of screening was 6.5 (3.0–10), 4.8 (3.2–10) and 5.6 (2.8–10) years, respectively. The number of patients who developed tumours in total was 11, 2 and 6 for SDHB, SDHC and SDHD patients, respectively. The percentage of patients who developed tumours was 31%, 33% and 67% for SDHB, SDHC and SDHD patients, respectively. Patients who were diagnosed with tumours on surveillance programme were 4, 2 and 3 for SDHB, SDHC and SDHD patients, respectively. The total number of tumours was 13, 3 and 13 for SDHB, SDHC and SDHD patients, respectively. The number of functioning HNPGL was 1 (1), 2 (1) and 12 (10) for SDHB, SDHC and SDHD patients, respectively. The number of functioning sPGL was 0, 0 and 0 for SDHB, SDHC and SDHD patients, respectively. The number of Phaeochromocytoma was 1, 0 and 1 for SDHB, SDHC and SDHD patients, respectively.

*No statistical difference between the SDHB, SDHC and SDHD groups.*
of the screening period, defined as the time of death (n=2) or May 2015 (n=45), there was no difference in the mean age between patients with different SDH subunit mutations (SDHB 46.9±17.6 years, SDHC 42.3±24.4 years and SDHD 54.9±10.6 years, P=0.5) (this lack of difference may be due to lack of power) (Table 1). There were seven different SDHB mutations, one SDHC and two different SDHD mutations. Mean duration of monitoring for all patients was 6.4 years (range 3.1–10.0 years).

Overall, at any time, 18 patients (12 index cases and six screened relatives) developed either sPGL or HNPG (SDHB 31% (11/36), SDHC 33% (2/6) and SDHD 100% (5/5)) (Tables 1 and 2). Patients with SDHB mutations predominantly developed sPGLs. Patients with SDHD mutations exclusively developed HNPGs (5/5 patients) and had multifocal disease (5/5) (Table 2). The youngest age at first presentation was 12 years (SDHD) and 15 years (SDHB). At the time of diagnosis of the first tumour, the median age was

Table 2 List of patients with SDHx subunit mutations who developed tumours with characteristics of disease and treatment.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Mutation</th>
<th>Age</th>
<th>Tumours</th>
<th>Secretion</th>
<th>Recurrent/multiple or metastatic</th>
<th>Size of tumour (cm)*</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>SDHB c.72 + 1G&gt;T</td>
<td>15</td>
<td>Pelvic sPGL</td>
<td>NA</td>
<td>No</td>
<td>4.0</td>
<td>Excision</td>
</tr>
<tr>
<td>2**</td>
<td>SDHB c.600G&gt;T</td>
<td>17</td>
<td>Pelvic sPGL</td>
<td>NA</td>
<td>No</td>
<td>4.0</td>
<td>Excision</td>
</tr>
<tr>
<td>3*</td>
<td>SDHB exon 1 deletion</td>
<td>50</td>
<td>Abdominal sPGL</td>
<td>NA</td>
<td>Locally aggressive</td>
<td>3.9</td>
<td>g-knife radiosurgery</td>
</tr>
<tr>
<td>4*</td>
<td>SDHB c.137G&gt;A</td>
<td>31</td>
<td>Abdominal sPGL</td>
<td>NA and DA</td>
<td>No</td>
<td>7.0</td>
<td>Excision</td>
</tr>
<tr>
<td>5*</td>
<td>SDHB c.379dupA</td>
<td>25</td>
<td>Abdominal sPGL</td>
<td>NA and DA</td>
<td>No</td>
<td>5.0</td>
<td>Excision</td>
</tr>
<tr>
<td>6**</td>
<td>SDHB c.379dupA</td>
<td>22</td>
<td>Abdominal sPGL</td>
<td>NA</td>
<td>Multiple (n=2)</td>
<td>2.0</td>
<td>Excision</td>
</tr>
<tr>
<td>7</td>
<td>SDHB c.379dupA</td>
<td>20</td>
<td>Thoracic sPGL</td>
<td>No</td>
<td>No</td>
<td>2.4</td>
<td>Excision</td>
</tr>
<tr>
<td>8</td>
<td>SDHB c.379dupA</td>
<td>68</td>
<td>Thoracic sPGL</td>
<td>No</td>
<td>No</td>
<td>1.2</td>
<td>Monitoring for 7 years, no change</td>
</tr>
<tr>
<td>9*</td>
<td>SDHB c.380T&gt;G</td>
<td>44</td>
<td>Thoracic sPGL</td>
<td>NA</td>
<td>No</td>
<td>3.7</td>
<td>w自治性放射外科手術</td>
</tr>
<tr>
<td>10*</td>
<td>SDHB c.17_42dup26</td>
<td>35</td>
<td>Thoracic sPGL</td>
<td>No</td>
<td>Metastatic (liver spine)</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>11+</td>
<td>SDHB c.17_42dup26</td>
<td>70</td>
<td>Abdominal sPGL</td>
<td>NA</td>
<td>No</td>
<td>5.0</td>
<td>Excision</td>
</tr>
<tr>
<td>12+</td>
<td>SDHC c.397C&gt;T</td>
<td>37</td>
<td>Abdominal sPGL</td>
<td>NA</td>
<td>Locally aggressive, progressive disease</td>
<td>&gt;5.3</td>
<td>Subtotal excision, excision of recurrence, g-knife radiosurgery</td>
</tr>
<tr>
<td>13</td>
<td>SDHC c.397C&gt;T</td>
<td>69</td>
<td>Recurrence of HNPG</td>
<td>DA</td>
<td></td>
<td>2.2</td>
<td>HNPG: excision</td>
</tr>
<tr>
<td>14+</td>
<td>SDHD c.342T&gt;A</td>
<td>40</td>
<td>HNPGs (bilateral CB)</td>
<td>No</td>
<td>Multiple (n=2)</td>
<td>2.1</td>
<td>sPGL: monitoring-mild increase in 5 years</td>
</tr>
<tr>
<td>15</td>
<td>SDHD.c.242C&gt;T</td>
<td>12</td>
<td>HNPG (GJ)</td>
<td>No</td>
<td>Multiple (n=3)</td>
<td>R: (NK), L: 1.8</td>
<td>Right CB: excision, Left CB: monitoring</td>
</tr>
<tr>
<td>16+</td>
<td>SDHD.c.242C&gt;T</td>
<td>22</td>
<td>HNPG (GJ)</td>
<td>No</td>
<td>Recurrent, multiple (n=3)</td>
<td>1.5</td>
<td>GJ: excision, g-knife radiosurgery</td>
</tr>
<tr>
<td>17</td>
<td>SDHD.c.242C&gt;T</td>
<td>31</td>
<td>HNPG (CB)</td>
<td>No</td>
<td>Recurrent, multiple (n=2), locally aggressive (GJ)</td>
<td>R: 2.2, L: 2.7</td>
<td>CB: monitoring</td>
</tr>
<tr>
<td>18</td>
<td>SDHD.c.242C&gt;T</td>
<td>56</td>
<td>HNPG (bilateral CB)</td>
<td>No</td>
<td>Multiple (n=2)</td>
<td>(NK)</td>
<td>CB: excision</td>
</tr>
</tbody>
</table>

*Index case; **Index case with second tumour; *sPGL on imaging, no histology; *maximum diameter by rapid-sequence MRI (maximum diameter by diagnostic imaging).

CB, carotid body tumour; DA, dopamine; GJ, glomus jugulare; L, left; NA, noradrenaline; NK, not known; R, right.
Clinical Study

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(All patients (index)): SDHB 28 years old (28), SDHD 31 years old (31).

Rapid-sequence MRI surveillance

Out of 47 patients, 43 underwent surveillance imaging with rapid-sequence MRI including all 12 index patients; four patients did not have MRI scans due to severe claustrophobia or non-attendance, were imaged by CT and were excluded from the analysis. Excluding any imaging performed during the diagnosis of the index tumours, imaging was performed on the surveillance protocol in the remaining 43 patients who underwent 116 rapid-sequence MRI scans: 83 scans were negative for sPGL/HNPGL and 31 were positive in 13 patients (Fig. 1). At the end of the study, there were no cases of missed PGLs, that is, in patients who developed tumours after the first surveillance MRI (n=4; two noradrenaline-secreting sPGLs, one HNPGL confirmed with US and one thoracic non-secreting sPGL confirmed with dedicated MRI imaging), none of the tumours were found to be present on re-review of earlier imaging. A number of radiological tests were performed in patients who had a positive MRI either for further characterization of positive findings or for disease monitoring (CT (eight scans from six patients), USS neck (15 scans from six patients), MIBG (4) and 18FDG PET CT (8)) (Table 3). USS neck was used to monitor the size of HNPGLs. Rapid-sequence MRI screening was repeated every 27±9 months (median 25 months) and the majority of patients had more than one scan during surveillance (n=number of patients (number of rapid-sequence MRI scans during surveillance)); n=9 (2), n=20 (3), n=6 (4), n=1 (6). The maximum diameter of new tumours diagnosed during surveillance with rapid-sequence MRI ranged between 0.6 and 3.5 cm, with no differences in imaging characteristics between SDHB, SDHC and SDHD subunit mutations.

Index cases

Out of 12 index patients, six had complete surgical resection of sPGLs (all noradrenaline-secreting) confirmed with histology before this study, normal biochemistry and a negative initial rapid-sequence MRI scan at surveillance baseline. Two patients (SDHB) were diagnosed with new sPGLs at the second surveillance MRI (noradrenaline-secreting) and were referred for surgical treatment (Fig. 2 and Table 2).

Four index cases with non-metastatic PGLs were not tumour-free on embarking on surveillance (subtotal resection due to multiple HNPGLs/extensive disease...
(n=3, patients 12, 14, 16) or non-resected disease (n=1, patient 9)). The rapid-sequence MRI was used to follow the size of tumours and detect new disease in this group of patients; one patient developed progressive disease and was referred for surgery (patient 12), two patients with HNPGLs (glomus jugulare) showed slow increase in the tumours and referred for radiosurgery (patients 14, 16) and one patient has stable disease (patient 9, sPGL).

There has been histological confirmation of sPGL/HNPGL in all patients who had surgical treatment and in one patient with metastatic disease who had a biopsy (n=10). Although histological confirmation was not made in two other patients, one has a functioning sPGL with characteristic imaging features and diagnostic biochemistry (patient 9) and one patient has a large glomus jugulare tumour with typical radiological features that has been treated with radiosurgery (patient 15). In each case, surgical treatment was either refused by the patient or not appropriate respectively.

Genetically screened relatives

During surveillance, six genetically screened relatives were diagnosed with either a solitary (n=4) or multiple (n=2) paraganglioma(s) on rapid-sequence MRI. The majority of patients (5/6) were diagnosed with PGLs during their first MRI scan (patients 7, 13, 15, 17 and 18). All tumours were non-functioning and there was confirmation from histology (patient 7) or additional dedicated imaging. Except from one patient who underwent surgical excision (patient 7), the tumours were not resected in the remaining four because of the anatomical position, and subsequent MRI scans were used to monitor size and plan management (see below). In one patient (patient 8), a small (0.6 × 1.2 cm) thoracic non-functioning sPGL was demonstrated at the second surveillance MRI, 28 months after an initial negative scan. The size of this tumour was also monitored by rapid-sequence MRIs due to the patient not wanting surgical intervention (Fig. 2 and Table 2).

Histological confirmation of a PGL has been made in all genetically screened relatives that had resection in whom the rapid-sequence MRI was deemed consistent with a PGL (n=5). There are two patients with small thoracic non-secreting PGLs who have not had surgery (patients 8 and 13, see below). The diagnosis of sPGL in these patients is based on typical MRI features; FDG-PET was positive in one patient and negative in the second.

Treatment

Surgical treatment was offered to all patients with non-metastatic sPGL (n=10 patients that developed 12 sPGLs). Overall, nine sPGLs were excised in seven patients (all SDHB), one patient with metastatic disease (SDHB) was treated with chemotherapy and radiotherapy (patient 10), and the disease was monitored with imaging and biochemistry in three patients (two SDHB, one SDHC; patients 8, 9 and 13) (Table 2), with strong patient preference the reason for monitoring instead of surgical treatment; in two patients with non-secreting thoracic sPGLs (patients 8 and 13), this decision was influenced by the high surgical risk due to the presence of co-morbidities and the anatomical challenges of the surgery. There were nine carotid body (CB) tumours in five patients; four patients were managed conservatively with imaging to assess tumour size because of previous surgery for a contralateral CB tumour (n=3, SDHD) and patient preference (n=1, SDHD). Five patients with glomus jugulare tumours (four index cases) were treated with gamma knife stereotactic radiosurgery (one SDHB, one SDHC and three SDHD; patients 3, 12, 14, 15 and 16). One patient with a noradrenaline-secreting glomus tumour causing local pressure symptoms had gamma knife stereotactic surgery as surgical intervention was
considered high risk (patient 3). Following treatment, there was a gradual decrease in the level of catecholamines, with symptoms improved and imaging, which showed reduction in tumour size within 2 years of intervention. A second patient (patient 12, SDHC mutation) with a large HNPGL with intracranial extension was treated with a combination of tumour embolization, surgical resection and radiosurgery to a small bone remnant. Three patients (patients 14, 15 and 16) with multifocal HNPGLs had imaging surveillance followed by gamma knife therapy when an increase in tumour size was detected. Overall, gamma knife therapy led to growth arrest in 4/5 cases and tumour volume reduction in 1/5 and no complications from this intervention in up to 5 years of follow up.

**Discussion**

An increasing number of patients presenting with paragangliomas are being diagnosed with SDHx mutations as genetic testing became standard clinical practice and need surveillance (18) to identify tumours at an early stage when they are amenable to surgical treatment and cure (16). As malignant tumours have been described in children and adolescents, it is common clinical practice to offer genetic testing to relatives of affected individuals from around the second decade of life, with mutation carriers then being offered clinical, radiological and biochemical screening (15, 19). For such lifelong screening, it is, therefore, important to minimize cumulative radiation exposure. Recent clinical guidelines emphasize the need for surveillance (17, 20). Our data support the use of rapid-sequence MRI for this purpose.

The clinical spectrum of paragangliomas is diverse. Without a clinical screening programme, mutation carriers are at a risk of presenting late with complications of syndromes relating to catecholamine excess, local pressure effects of tumours and malignant and metastatic disease (21). Most tumours are, however, non-functioning and therefore biochemical and clinical monitoring alone is not enough. Measurement of free plasma metanephrines has been reported to be the most sensitive test for functional paragangliomas and phaeochromocytomas (22) combined with the measurement of the dopamine metabolite 3-methoxytyramine as some paragangliomas produce only dopamine (Table 2) (23). For these reasons, our surveillance protocol mandates yearly biochemical and clinical assessment.
There is a debate as to the gold standard for the detection of paragangliomas. A recent large French series of \(SDHx\) mutation carriers showed that a combination of imaging modalities (body CT, Head and neck MRA and octreotide scintigraphy) was 99\% sensitive for paraganglioma detection (24); a sub-analysis of the MRA scans from this study showed that a simplified shorter angio-MRI protocol had similar diagnostic performance to the full imaging protocol and could be used instead for the detection of HNPGLs (25). Although CT has an excellent sensitivity, it involves the use of ionizing radiation and is not ideal for lifelong surveillance. MRI does not involve ionizing radiation and is acceptable for use in younger patients and females of reproductive age, making it an ideal surveillance imaging modality for individuals with \(SDHx\) mutations. Shorter scanning protocols to reduce scanning time of whole body MRI have been developed and cross-sectional data show these to be effective in this clinical setting (26). Functional imaging can further characterize any tumour and assess for multifocal or metastatic disease (27). In this context, \(^{18}\text{F}\)-FDG-PET has been used for several years in patients with \(SDHB\) mutations and metastatic disease (28), but recently \(^{68}\text{Ga}\)-DOTATATE PET/CT has been shown to be superior (29). Other compounds such as \(^{18}\text{F}\)-fluorodopamine (\(^{18}\text{F}\)-FDA) and \(^{18}\text{F}\)-fluorodihydroxyphenylalanine (\(^{18}\text{F}\)-FDOPA) have great promise but are not currently widely available (30). Although \(^{123}\text{I}\)-MIBG imaging is less sensitive than these modalities, it offers a therapeutic option (\(^{131}\text{I}\)-MIBG) in MIBG-avid patients with metastatic disease (28, 31).

Our rapid MRI sequences minimize time (skull base to symphysis pubis scanned in less than half an hour), cost (intravenous gadolinium contrast is not used) and provides accurate results; we have not identified a missed case of a paraganglioma using this rapid-sequence MRI for 10 years. Furthermore, our data show that this technique can be used reliably to detect new tumours as well as to monitor tumour growth in patients managed conservatively. Because the majority of tumours detected in our cohort were on first screening of mutation carriers, we suggest that all index case relatives with a positive genetic test are offered imaging at the earliest opportunity, as this is the most likely time that tumours will be detected. For patients who had negative initial screening, use of rapid-sequence MRI approximately every 2 years appears to be effective and clinically safe. Patients with known tumours under surveillance should have individualized follow-up. An association of pituitary tumours and \(SDHx\) has been proposed (32), and our MRI protocol allows detection of pituitary tumours of size significant enough to pose a clinical management discussion. Other than the likelihood of the anatomic location of tumours, we found no differences in the MRI features of tumours due to \(SDHB\), \(SDHC\) or \(SDHD\) mutations.

Gamma knife radiosurgery appears to be an effective treatment option for some patients with HNPGLs where surgery would carry too much morbidity, including those with a previous history of neck surgery (where the predicted postoperative neurological complications are significant) and older patients with significant perioperative risk (33). While we report good outcomes from gamma knife radiosurgery, it is important to note that we are the National Centre for Stereotactic radiosurgery and have treated more than 15,000 patients with this technique; it is likely that this high level of expertise had a positive impact on our patient outcomes, and good outcomes and low complications are reported from other high-volume centres (34).

The strengths of this study are that it is a single-centre study with extensive relevant imaging and clinical expertise, where a practical rapid-sequence MRI imaging protocol has been developed and used for screening for over 10 years, with all cases routinely discussed in multidisciplinary meetings in the presence of endocrine surgeons and input from all specialists’ informed management decisions. Although small tumours (<5 mm) may suffer from partial volume effects limiting the interpretation, the likelihood of tumours of this size causing a clinical syndrome associated with catecholamine excess or being of malignant potential is low. Limitations of our study include the need for multidisciplinary expertise. Although this is a large cohort, the numbers of patients with positive scans remain small precluding statistical comparisons. Furthermore, a single gold standard test that can be used for long-term screening in these patients does not exist, and there is no imaging modality (or combination of modalities) that is without significant radiation exposure and could be used as a comparison; therefore, the outcome of the review of biochemistry, clinical data and MRI imaging by the multidisciplinary team was considered the gold standard to determine the success of treatment and disease-free status. Finally, although two of the patients we describe (patients 8 and 13) have typical radiological features of
sPGLs, their biochemistry was normal and they have declined surgery, and thus we do not have histological confirmation for them.

To our knowledge, this is the first report of longitudinal screening in patients with SDHx mutations using non-contrast rapid-sequence MRI. Our data support the use of this technique in the surveillance of these patients to detect new tumours and monitor size of existing tumours and provide evidence that biannual imaging with annual biochemical testing is an effective approach.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Author contribution statement
E D and J N P analysed the data and wrote the manuscript and all authors edited the manuscript. M B reviewed all radiological data. E D and R J collected the data.

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