The idiopathic congenital central hypoventilation syndrome (CCHS) was first described by Mellins et al. and is characterised by an alteration of the ventilatory response to hypercapnia and hypoxia. Whereas normal ventilation is adequate in many of the patients during wakefulness, the alveolar hypoventilation observed during sleep seems attributable to a failure of the central autonomic control of ventilation in the brainstem. CCHS is a rare entity in which affected children show symptoms typically in the newborn period. These symptoms include a period of cyanosis upon sleep induction, a decrease of oxyhaemoglobin saturation with simultaneous life threatening increase of the partial pressure of CO2 in arterial blood (PaCO2), which yields no respiratory response, and no arousal reflex by the infants. Primary neuromuscular, lung, or cardiac disorders or an identifiable brainstem lesion are absent. The first extensive series of CCHS patients was described by Weese-Mayer et al. in 1992.

The apparent functional defect possibly stems from an abnormal migration or differentiation of neural crest derived cells into the autonomic ventilatory control system. Therefore, idiopathic congenital central hypoventilation syndrome may be regarded as a feature of complex neurocristopathies, as confirmed by the observation of a combination of CCHS and other neurocristopathies. Specifically, CCHS has been reported in association with neoplastic as well as dysgenetic neurocristopathies, such as neuroblastomas and ganglioneuromas, but the frequency of such cases is lower than 5%. Furthermore, in 16-20% of the patients, CCHS is combined with Hirschsprung disease (HSCR), a developmental central hypoventilation disorder characterised by congenital absence of ganglion cells in the myoenteric and submucosal plexuses of the bowel.

Although most CCHS cases are sporadic, a putative genetic origin for CCHS has also been considered because of the familial occurrence in several reported cases, such as monozygotic female twins, female sibs, male-female sibs, and male-female half sibs. Moreover, a case-control family study showed that CCHS patients and their parents are more likely to be affected with symptoms of autonomic nervous system dysfunction (ANSD) than controls and parents of controls. Thus, CCHS is also considered as the most severe manifestation of ANSD. The segregation analysis of ANSD symptoms in families with CCHS affected subjects was consistent with the familial association hypothesis and fits almost equally two genetic models, the major locus model and the multifactorial model.

In addition to the frequently reported association of CCHS with Hirschsprung disease in humans, a similar phenotype has also been observed in the ret knockout mouse model. Whereas heterozygous animals did not show any histopathological signs of aganglionosis, animals with a homozygous functional ret deletion showed severe aganglionosis extending to the stomach and also variable defects of the kidneys. Interestingly, ret -/- mice died within the first 16-24 hours of life, probably not as a result of the above mentioned malformations but rather from altered respiratory CO2 sensitivity and responsiveness. In addition, reports of patients with HSCR who harbour germline mutations of the RET proto-oncogene have shown that they were primarily point mutations scattered throughout the extracellular domain and within the intracellular tyrosine kinase domain of RET in up to 20% of sporadic cases and in up to 50% of familial cases. However, a population based study of Swedish HSCR patients showed a low mutation rate of only 3.2%. The RET mutations found in HSCR result in either RET protein truncation, decreased presentation on cell surface, or functional inactivation of the molecule.

Based on these observations, the RET proto-oncogene may also be considered as a candidate gene for idiopathic congenital central hypoventilation syndrome, although previous analyses of the coding region of RET showed no causative mutation (apart from common gene variants at positions c.1296G/A, c.2071G/A, c.2307T/G, and c.2712C/G) in 17 CCHS patients, of whom seven showed a combination with

**Key points**

- The idiopathic congenital central hypoventilation syndrome (CCHS) is characterised by an alteration of the ventilatory response to hypercapnia and hypoxia resulting in a life threatening increase of PaCO2 during sleep. The reported association of CCHS with Hirschsprung disease in humans, and a similar phenotype observed in the ret knockout mouse model, support the RET proto-oncogene as a candidate gene for CCHS.

- We analysed the complete RET coding sequence in 33 unrelated patients with CCHS by direct DNA sequencing.

- In eight (24.2%), CCHS coexisted with Hirschsprung disease. We detected three RET germline mutations, which in two cases were inherited from asymptomatic parents. Additionally, we found an association of RET polymorphic variants with the CCHS phenotype. In particular, the association of the c.135A variant with CCHS was statistically significant.

- The identification of RET germline mutations in CCHS patients, as well as the association of specific RET variants with this phenotype, suggest that this gene contributes to the aetiology of CCHS. Nevertheless, the low mutation rate, incomplete penetrance, variable phenotype, and the involvement of other genes like GDNF, EDN3, or BDNF imply that there are further unidentified genes which may contribute to the aetiology of CCHS in a complex pattern of inheritance.
HSCR. In further studies on seven patients, and in an additional case report, two missense mutations of RET were detected in patients with the CCHS/HSCR association. Moreover, similar to the findings in HSCR patients, a missense mutation of the RET ligand GDNF and an EDN3 frameshift mutation were found in patients with isolated CCHS. In a recent sequencing analysis of the BDNF gene in 19 CCHS patients, a missense mutation was detected in a patient without HSCR but additional ANSD symptoms.

In this study we report the analysis of the coding RET sequence in CCHS patients, detecting three germline mutations in unrelated cases, of whom one had an isolated CCHS. Furthermore, we describe the allele frequencies of seven RET polymorphic variants and the association of the c.135A variant with the CCHS phenotype.

**MATERIALS AND METHODS**

Our population comprised 33 unrelated patients (31 from Germany, one from German Switzerland, and one from Austria) who were followed exclusively in specialised pulmonary care centres and met the criteria for CCHS, evaluated and diagnosed by a polygraphic respiratory recording which detected hypoventilation, high PaCO2, and low PaO2 during quiet sleep, and for whom the review of medical records yielded no further cause for the hypoventilation. None of them showed additional primary neuromuscular, pulmonary, or cardiac anomalies. Eight of the 33 patients (24.2%) had a concomitant HSCR phenotype. Hirschsprung disease was diagnosed by histological and histochemical evaluation of intestinal biopsies, confirming the absence of enteric ganglia and the increase in acetylcholinesterase in hyperplastic nerve fibres in the aganglionic tract.

One patient in our series had a monozygotic twin with the same clinical presentation of CCHS and another patient had an affected brother. All other patients were seemingly sporadic cases. Samples from previously described healthy German blood donors served as our normal, race and gender matched controls. According to a questionnaire, they did not have any symptoms of HSCR. The patient herself and the relatives investigated did not suffer from constipation, so we had no reason to evaluate the intestinal nervous system histologically.

**RESULTS**

Sequence analysis showed a **RET** germline mutation in a female patient with CCHS and central epilepsy, but without any symptoms of HSCR. The patient herself and the relatives investigated did not suffer from constipation, so we had no reason to evaluate the intestinal nervous system histologically. We found a nucleotide change (C>A) at position 654 of intron 12. This mutation was transmitted from the healthy father and we also detected this transversion in the asymptomatic brother.

Furthermore, we found a missense mutation of exon 13 codon 791 (TAT→TTT) in a male patient with CCHS in association with total colonic aganglionosis, which resulted in the substitution of a highly conserved tyrosine for phenylalanine. This Y791F mutation has been previously reported in a patient with sporadic HSCR, as well as in a kindred with familial medullary thyroid carcinoma. In our patient, the mutation was inherited from the unaffected father and the family history for HSCR or MEN2 was negative. A third mutation was detected in exon 14 codon 841 (CCG→CTG) in a female CCHS/HSCR patient with short segment aganglionosis. This hitherto unknown C→T transition resulted in the substitution of a proline by a leucine. This mutation was not detected in the healthy mother, while genetic testing was not possible in the father. None of these three mutations was detected in 120 normal controls (table 1).

In addition to the mutations, we found a rare **RET** variant of exon 18 codon 982 (CGC→TGC) in a male patient with combined CCHS and HSCR, which substituted a cysteine residue for an arginine. This variant was inherited from the healthy mother and was absent in 156 normal controls.

We have determined allele frequencies for seven **RET** polymorphisms in the CCHS population and compared the results to those in a normal control population. Only one of these

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**Table 1** **RET** germline mutations in 33 CCHS patients

<table>
<thead>
<tr>
<th>Patient</th>
<th>Exon/Intron</th>
<th>Mutation</th>
<th>Nucleotide</th>
<th>Alteration in sequence</th>
<th>Evolutionary conservation</th>
<th>HSCR (phenotype)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>IVS12 + 54C&gt;A</td>
<td>C to A</td>
<td>Missense M, C† Long</td>
<td>No HSCR</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>P841L</td>
<td>CCG to CTG</td>
<td>Missense M* Short</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>Y791F</td>
<td>TAT to TTT</td>
<td>Missense M, C† Long</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*M = mouse. †C = chicken.
seven polymorphisms showed a statistically significant association with the CCHS phenotype. The genotype distribution for each of the seven polymorphic loci did not deviate significantly from Hardy-Weinberg equilibrium.

A significant over-representation of the c.135A variant was found within the CCHS population in comparison to the controls (table 2, $\chi^2=4.536, p=0.034$). Furthermore, a similar tendency towards over-representation of the c.1296A variant of RET was found in the CCHS population, although the difference was not statistically significant (table 2, $\chi^2=3.656, p=0.074$). The allele frequencies of all other investigated polymorphisms, namely those of codons c.375C/A, c.2071G/A, c.2307T/G, c.2508C/T, and c.2712C/G, did not derive from that polymorphisms, namely those of codons c.375C/A, c.2071G/A, c.2307T/G, c.2508C/T, and c.2712C/G, did not derive from that polymorphism in three out of 142 normal chromosomes. Sancandi et al. detected the heterozygous codon 982 variant in five out of 57 sporadic HSCR patients and Svensson et al. detected it in a sporadic HSCR patient who harbours an additional EDNRB mutation.

Although this variant is detected in controls and the phosphorylation activity of the RET molecule is not altered, it is considered not as a mutation but as a polymorphism. However, the possibility remains that this polymorphism increases the risk of developing the HSCR or CCHS/HSCR phenotype by interfering with RET expression rather than with RET function.

We also found an association of a polymorphic RET variant with idiopathic congenital central hypoventilation syndrome. In particular, the c.135A variant is significantly over-represented in our CCHS population compared to normal controls. Although the statistical significance of this association is weak, this finding agrees with the strong association of this variant with the HSCR phenotype, as previously reported. Interestingly, none of the c.2071G/A, c.375C/A, c.2071G/A, c.2307T/G, c.2508C/T, and c.2712C/G, did not derive from that detected in our normal control population, which was matched for race and gender (table 2).

**DISCUSSION**

In this study, we investigated 25 patients with isolated CCHS and eight patients with CCHS in combination with HSCR for RET germline mutations in the 21 exons including the adjacent intronic sequences. We detected three germline mutations, one in a patient with a CCHS/epilepsy phenotype but no HSCR and two in patients with a CCHS/HSCR phenotype. Several studies have reported 25 CCHS patients in total comprising 10 patients with a combined CCHS/HSCR phenotype, but RET germline mutations were reported solely in CCHS patients in association with HSCR. Amiel et al. found a heterozygous P1039L mutation in a CCHS/HSCR patient who had inherited the mutation from the unaffected father, and Sakai et al. also described a heterozygous T706A mutation in a CCHS/HSCR patient.

We report a RET mutation in a patient with isolated CCHS/epilepsy phenotype. Although it was located in position ds+54 of intron 12, we did not find this variant in our normal control population. Intronic mutations close to this variant have been reported in association with HSCR. Since the mutation derives from a C→A transversion, we hypothesise that it could generate a new splice acceptor site.

Furthermore, we describe a new P841L mutation in a CCHS/HSCR patient. Interestingly, the same amino acid change was found in codon 1039 of a CCHS/HSCR patient by Amiel et al. In addition, the substitution of a leucine for a proline amino acid residue was reported in association with isolated HSCR for codons 20, 64, 399, and 973. In addition to the frequent occurrence of this substitution, all of these proline residues are conserved between humans and mice.

Besides the mutations, a rare RET variant of exon 18 codon 982 was found in a patient with combined CCHS and HSCR. This variant was not detected in our 312 control chromosomes, but Mulligan et al. found this polymorphism in three out of 142 normal chromosomes. Sancandi et al. detected the heterozygous codon 982 variant in the isolated CCHS population, although the difference was not statistically significant (table 2, $\chi^2=3.656, p=0.074$). The allele frequencies of all other investigated polymorphisms, namely those of codons c.375C/A, c.2071G/A, c.2307T/G, c.2508C/T, and c.2712C/G, did not derive from that detected in our normal control population, which was matched for race and gender (table 2).

**Table 2** Allele frequencies of polymorphic variants of RET in 33 CCHS patients and 156 controls

<table>
<thead>
<tr>
<th>Exon/intron</th>
<th>Nucleotide change/codon position</th>
<th>Restriction site changed</th>
<th>Allele frequency*</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control population</td>
<td>CCHS population</td>
</tr>
<tr>
<td>Exon 2</td>
<td>GGC to GCA, c.135G/A</td>
<td>Eagl</td>
<td>76.3%</td>
<td>63.6%</td>
</tr>
<tr>
<td>Exon 3</td>
<td>GTC to GTA, c.375C/A</td>
<td>Mbol</td>
<td>98.1%</td>
<td>100%</td>
</tr>
<tr>
<td>Exon 7</td>
<td>GGC to GCA, c.1296G/A</td>
<td>BsmI</td>
<td>72.4%</td>
<td>60.6%</td>
</tr>
<tr>
<td>Exon 11</td>
<td>GTC to AGT, c.2071G/A</td>
<td>BsmI</td>
<td>79.8%</td>
<td>80.3%</td>
</tr>
<tr>
<td>Exon 13</td>
<td>CTT to CTG, c.2307T/G</td>
<td>TaqI</td>
<td>76.3%</td>
<td>71.2%</td>
</tr>
<tr>
<td>Exon 14</td>
<td>AGC to AGT, c.2508C/T</td>
<td>AluI</td>
<td>96.4%†</td>
<td>93.9%</td>
</tr>
<tr>
<td>Exon 15</td>
<td>TCC to TCG, c.2712C/G</td>
<td>KpnI</td>
<td>80.1%</td>
<td>81.8%</td>
</tr>
</tbody>
</table>

*Allele frequencies of the wild type allele, which is underlined in the column “Nucleotide change/codon position”.
†For the c.2508 polymorphism only 153 controls were tested.
‡For the intron 2 ds+9 polymorphism only 114 controls were tested.
controls and their families, these findings support the hypothesis of an involvement of specific RET haplotypes in the aetiology of CCHS and HSCR.

Additionally, functional identification of additional RET germline mutations in CCHS patients and the association of a specific RET variant with this phenotype suggest a contribution of RET to the aetiology of CCHS as the most severe form of ANS dysfunction. However, the low mutation rate, the incomplete penetrance, the variable phenotype, and the involvement of other genes like GDNF, EDN3, or BDNF further suggest that additional unidentified genes may be present, involved in the aetiology of idiopathic congenital central hyperventilation syndrome in a complex multicogenic pattern of inheritance, in which a cumulative effect of mutations in multiple genes contributes to the phenotype.

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