

A review of craniofacial and dental findings of the RASopathies

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Funding information

National Institute of Dental and Craniofacial Research, Grant/Award Number: K12-DE023574 and R35-DE026602; American Association of Orthodontists Foundation, Grant/Award Number: PFA; Chinese Scholarship Council.

Objectives: The RASopathies are a group of syndromes that have in common germline mutations in genes that encode components of the Ras/mitogen-activated protein kinase (MAPK) pathway and have been a focus of study to understand the role of this pathway in development and disease. These syndromes include Noonan syndrome (NS), Noonan syndrome with multiple lentigines (NSML or LEOPARD syndrome), neurofibromatosis type 1 (NF1), Costello syndrome (CS), cardio-facio-cutaneous (CFC) syndrome, neurofibromatosis type 1-like syndrome (NFLS or Legius syndrome) and capillary malformation-arteriovenous malformation syndrome (CM-AVM). These disorders affect multiple systems, including the craniofacial complex. Although the craniofacial features have been well described and can aid in clinical diagnosis, the dental phenotypes have not been analysed in detail for each of the RASopathies. In this review, we summarize the clinical features of the RASopathies, highlighting the reported craniofacial and dental findings.

Methods: Review of the literature.

Results: Each of the RASopathies reviewed, caused by mutations in genes that encode different proteins in the Ras pathway, have unique and overlapping craniofacial and dental characteristics.

Conclusions: Careful description of craniofacial and dental features of the RASopathies can provide information for dental clinicians treating these individuals and can also give insight into the role of Ras signalling in craniofacial development.

KEYWORDS

craniofacial development, dental anomalies, malocclusion, Ras/MAPK pathway, RASopathy

1 | INTRODUCTION

The RASopathies are a class of human genetic syndromes caused by germline mutations in genes that encode components of the Ras/mitogen-activated protein kinase (MAPK) pathway.¹ The Ras pathway is an essential signalling cascade that controls many aspects of cell behaviour, including proliferation, differentiation and survival.² The RAS genes, *HRAS*, *NRAS* and *KRAS*, encode small, monomeric GTPases that are activated by upstream regulators, including receptor tyrosine kinases (RTKs), G-protein-coupled receptors and integrins. Once activated, Ras-GTP conveys the extracellular signal through multiple effector pathways, including Raf/MEK/ERK and PI3K/AKT (Figure 1).

The RASopathies include (i) Noonan syndrome (NS), (ii) Noonan syndrome with multiple lentigines (NSML or LEOPARD syndrome), (iii) neurofibromatosis type 1 (NF1), (iv) Costello syndrome (CS), (v) cardio-facio-cutaneous (CFC) syndrome, (vi) neurofibromatosis type 1-like syndrome (NFLS or Legius syndrome) and (vii) capillary malformation-arteriovenous malformation syndrome (CM-AVM). Altogether, the RASopathies represent one of the most prevalent groups of developmental malformation syndromes, affecting more than 1 in 1 000 individuals.³ Although each of the RASopathies is a distinct syndrome caused by mutations at different points in the pathway, these syndromes share many overlapping characteristics, including craniofacial dysmorphology, cardiovascular abnormalities,

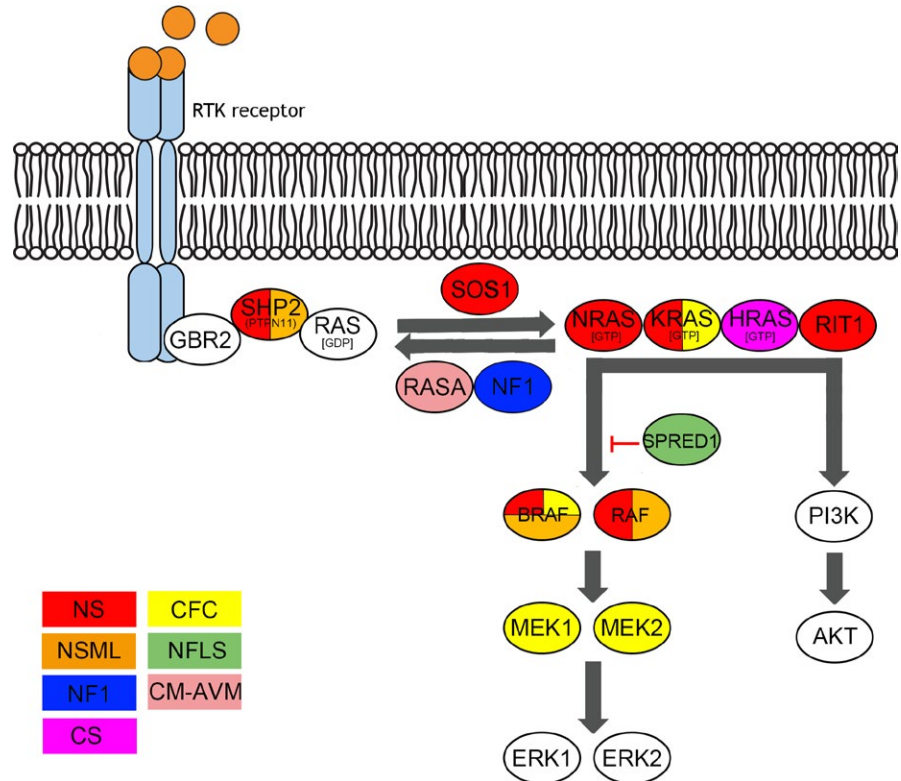


FIGURE 1 Syndromes of the Ras pathway. Schematic representation of the Ras signalling pathway. Each syndrome is represented by a colour, and the protein in the pathway encoded by the causative mutated gene is illustrated in that colour.

musculoskeletal anomalies, cutaneous lesions, neurocognitive impairment and increased risk of tumour formation.⁴ In the craniofacial complex, each syndrome has common and distinct features, and well-delineated craniofacial characteristics aid in clinical diagnosis of the RASopathies prior to genetic testing. Characterization of the craniofacial and dental features can also provide insight into the role of the Ras pathway in craniofacial development. For example, determining which of the RASopathies has a particular malocclusion and correlating the malocclusion to the disrupted gene has the potential to increase our understanding of the genetics underlying malocclusion and advance personalized orthodontics. In this review, we summarize the clinical characteristics and genetic aetiologies of each of the most common RASopathies, emphasizing the craniofacial and dental features of these syndromes (summarized in Table 1).

1.1 | Noonan syndrome (NS)

NS (OMIM 163950) is a relatively common, autosomal dominant inherited disorder with a prevalence between 1:1 000 and 1:2 500 live births. Individuals with NS typically have reduced postnatal growth and short stature, congenital heart defects, including hypertrophic cardiomyopathy (HCM), skeletal anomalies and cognitive deficits.^{5,6} NS is a genetically heterogeneous disorder, and germline mutations in more than 10 genes have been associated with the syndrome. The three genes primarily affected in NS are *PTPN11*, mutated in ~50% of cases, *SOS1* (~10%) and *RAF1* (5%-10%).⁷ NS is less frequently associated with mutations in *KRAS*, *NRAS*, *BRAF*, *SOS2*, *RASA2*, *LZTR1*, *RRAS* and *RIT1*.^{1,8,9}

Craniofacial features of NS include relative macrocephaly, distinctive “triangular facies” with high forehead, hypertelorism and pointed chin, downslanting palpebral fissures, epicanthal folds, ptosis and low-set posteriorly rotated ears with thickened helices (Figure 2A,B). Other NS craniofacial features include short and/or webbed neck and a low posterior hairline. Although rare, benign multiple giant cell lesions (MGCLs) of hard and/or soft tissues have been reported to develop in the craniofacial region of NS individuals. MGCLs are associated with jaw enlargement in 46% of affected individuals, and lesions of the mandible, and to a lesser extent of the maxilla, are first detected between ages 2 and 19 years.^{10,11}

Oral findings in NS individuals, reported in case studies, include micrognathia, high-arched palate, dental malocclusion, impacted teeth and giant cell lesions in the maxilla and mandible.¹² In a cohort of mutation-positive NS subjects (N=20), we noted a normal distribution of class I occlusion and class II malocclusion and increased incidence of open bite (29%; $P=.0001$) and posterior crossbite (30%; $P=.0001$) compared to the general population (Figure 3A,B). More severe dental phenotypes have been reported, including a case report of a 13-year-old boy with multiple unerupted permanent teeth, multiple submerged and retained deciduous teeth and supernumerary teeth.¹³

1.2 | Noonan syndrome with multiple lentigines (NSML or LEOPARD syndrome)

NSML (OMIM 151100) is a rare, autosomal dominant genetic disorder that overlaps phenotypically with NS. The prevalence of NSML

**TABLE 1** Craniofacial and dental findings of the RASopathies

Syndrome	Associated genes	Craniofacial findings	Dental findings	References for craniofacial and dental findings
Noonan syndrome (NS)	<i>PTPN11, SOS1, RAF1, KRAS, NRAS, BRAF, SOS2, RASA2, LZTR1, RRAS, RIT1</i>	Relative macrocephaly, "triangular facies" with high forehead, hypertelorism and pointed chin, downslanting palpebral fissures, epicanthal folds, ptosis, low-set posteriorly rotated ears, short and/or webbed neck, low posterior hairline	High-arched palate, open bite, posterior crossbite Case reports: multiple giant cell lesions in the jaws or soft tissues, multiple unerupted permanent teeth, multiple submerged and retained deciduous teeth, supernumerary teeth	10-13
NS with multiple lentiginos (NSML or LEOPARD syndrome)	<i>PTPN11, RAF1, BRAF</i>	NS-like facies, multiple lentiginos and café-au-lait spots on the face and neck, short neck with nuchal skin (usually not webbed), mandibular prognathism, macroglossia	Case reports: high-arch palate, missing primary and permanent teeth, mandibular osteolytic lesions, disrupted tooth eruption	17-19
Neurofibromatosis type 1 (NF1)	<i>NF1</i>	Neurofibromas in head and neck region, café-au-lait spots	Hypoplastic mandible, mandibular cysts, retained deciduous teeth, missing permanent teeth	22, 23
Costello syndrome (CS)	<i>HRAS</i>	Coarse facies, relative macrocephaly, high forehead, bitemporal narrowing, hypertelorism appearance, down slanting palpebral fissures, epicanthal folds, short nose with depressed bridge and wide nasal tip, full cheeks, large mouth, thick lips, low-set posteriorly rotated ears	High-arched palate, thickening of alveolar ridge, class III malocclusion, open bite, posterior crossbite, gingival hypertrophy, delayed tooth development and eruption, enamel defect	25, 26
Cardio-facio-cutaneous syndrome (CFC)	<i>KRAS, BRAF, MAP2K1, MAP2K2</i>	Relative macrocephaly, high cranial vault and forehead, bitemporal narrowing, hypoplastic supraorbital ridges, hypertelorism appearance, short nose with depressed nasal bridge and wide nasal tip, low-set posteriorly rotated ears	High-arched palate, open bite, posterior crossbite	30
Neurofibromatosis type 1-like syndrome (NFLS or Legius syndrome)	<i>SPRED1</i>	Macrocephaly, hypertelorism, café-au-lait spots in head and neck region	Not reported	33
Capillary malformation-arteriovenous syndrome (CM-AVM)	<i>RASA1</i>	CM-AVMs in head and neck region	Intraosseous CM-AVMs in the maxilla and mandible may cause malocclusion, tooth mobility and gingival bleeding	35

is unknown; however, more than 200 patients have been reported.¹⁴ The syndrome was formerly referred to as LEOPARD syndrome, an acronym that describes the disorder: lentiginos, electrocardiographic conduction abnormalities, ocular hypertelorism, pulmonic valve stenosis, abnormal genitalia, retardation of growth and sensorineural deafness.¹⁵ In addition, features of NSML include cardiac abnormalities, particularly HCM, skeletal anomalies, cognitive deficits and café-au-lait macules. NSML is a genetically heterogeneous disorder caused by mutations in three genes: *PTPN11*, *RAF1* and *BRAF*.¹⁶

NSML individuals have NS-like facial features, although the features of NSML are considered to be milder than NS. In addition, craniofacial features of NSML include mandibular prognathism,

macroglossia and short, but usually not webbed, neck with nuchal skin.¹⁶ The characteristic multiple lentiginos, which are flat, black-brown macules, are primarily present on the face, neck and upper torso. Typically, lentiginos start to appear at the age of 4-5 years old and increase in number exponentially throughout childhood to reach into the thousands by puberty. Café-au-lait spots, or hyperpigmented lesions that vary in size and in colour from light to dark brown, are also observed, alone or in association with lentiginos, in up to 70%-80% of NSML individuals and usually precede the appearance of lentiginos.

The oral features of NSML have not been well delineated in the literature; however, case reports show variability in the dental

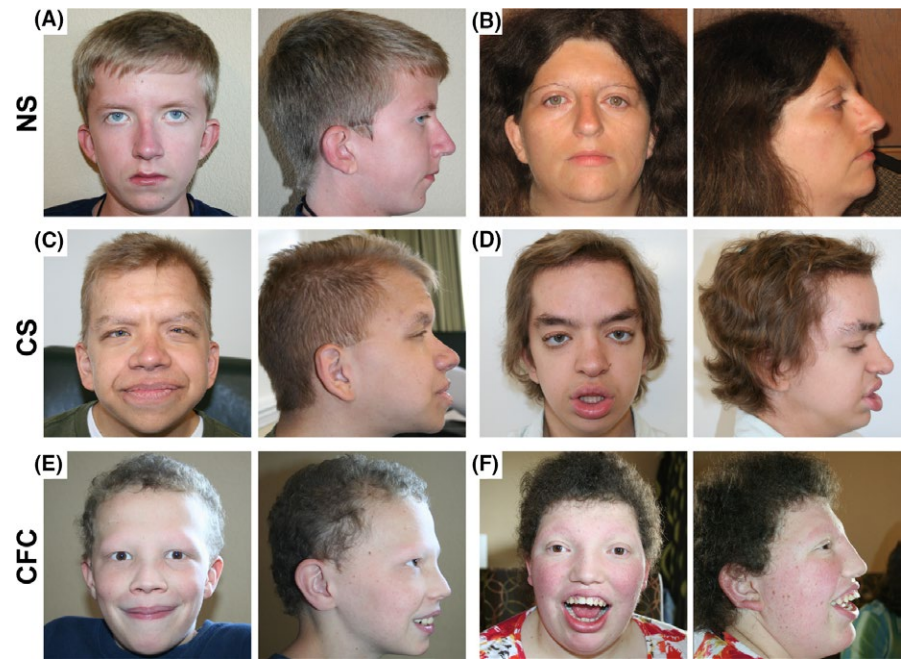


FIGURE 2 Craniofacial features of NS, CS and CFC. Frontal and profile photographs of (A) a 15-year-old male and (B) 31-year-old female with NS, (C) 26-year-old male and (D) 17-year-old female with CS and (E) 12-year-old male and (F) 17-year-old female with CFC.



FIGURE 3 Dental characteristics of NS, CS and CFC. (A,C,E) Open bite. Black arrows point to mamelons, which are normally abraded by contact. (B,D,F) Posterior crossbite (demarcated by white arrows). (B) Individuals with NS present with expected incidence of class I occlusion and class II malocclusion as shown by black arrow demarcating maxillary canine cusp tip anterior relative to the contact between the mandibular canine and first premolar (black line). (D) CS individuals have higher incidence of class III malocclusion with the maxillary canine (black arrow) posterior to the contact (black line) while (F) CFC individuals present with normal distribution of class I occlusion with the maxillary canine (black arrow) in line with the contact (black line) or class II malocclusion (as shown in B).

phenotype. One case report documented high-arched palate, primary maxillary central incisor caries, missing primary mandibular left lateral incisor and increased overjet.¹⁷ Dental anomalies such as maxillary lateral incisor and canine agenesis and decreased head circumference

have also been reported.¹⁸ A recent case study reported an NSML individual with bilateral facial swelling due to unusual mandibular osteolytic lesions with multiple osteoclastic-like giant cells and disrupted tooth eruption.¹⁹



1.3 | Neurofibromatosis type 1 (NF1)

NF1 (OMIM 162200) is an autosomal dominant disorder caused by mutations in the tumour suppressor gene *NF1*, with a prevalence of 1:3 000 live births.²⁰ The features of NF1 include dermatologic abnormalities, such as café-au-lait macules, ocular defects, including Lisch nodules, skeletal anomalies, such as dysplastic bony changes and cysts and neural defects, including optic pathway gliomas. The hallmark feature of NF1 is the development of plexiform neurofibromas, which are benign tumours of peripheral nerve sheaths. These tumours have the potential to transform into malignant peripheral nerve sheath tumours (MPNSTs) that affect 10% of NF1 individuals.²¹

The distinctive neurofibromas of NF1 can occur in the head and neck region. Although benign, these tumours are expansive and can cause deformities due to involvement of soft tissue and bones of the orbital, cranial and jaw regions; these are typically hemifacial but can also be bilateral.²² Café-au-lait spots can develop on the scalp and skin of the peri- and intra-orbital, maxillary and mandibular regions. Intraoral findings include dental irregularities, such as retained deciduous molars and congenitally missing mandibular second molars. There have been reports of hypoplasia of the mandibular body and ramus and abnormal coronoid process and zygomatic arch shape.²³ Mandibular cysts have also been reported, which resulted in mandibular expansion with convex outer contour and increased vertical height.²²

1.4 | Costello syndrome (CS)

CS (OMIM 218040) is a rare, multiple anomaly syndrome caused by activating, germline mutations in *HRAS* with severe failure to thrive, growth retardation, dermatologic abnormalities, heart defects, including HCM, musculoskeletal anomalies, intellectual disability and a preposition to malignancies; the prevalence is estimated to be 1:1 290 000.²⁴

CS individuals have a distinct “coarse” facial appearance that includes relative macrocephaly with high forehead, bitemporal narrowing, hypertelorism appearance, downslanting palpebral fissures, epicanthal folds, short nose with depressed bridge and wide nasal tip, full cheeks, large mouth, thick lips and low-set posteriorly rotated ears²⁵ (Figure 2C,D). Intraoral findings include high-arched palate and malocclusion with increased incidence of class III malocclusion, posterior crossbite and open bite (Figure 3C,D). Bifid uvula, gingival hypertrophy and thickening of the alveolar ridge have also been reported in CS. Additionally, CS individuals have delayed tooth development and eruption and a unique enamel defect characterized by thin, hypomineralized enamel.²⁶

1.5 | Cardio-facio-cutaneous (CFC) syndrome

CFC (OMIM 115150) is a rare (prevalence 1:810 000 live births²⁷), autosomal dominant, multiple congenital anomalies syndrome that significantly overlaps with NS and CS, making the clinical diagnosis challenging, particularly during the neonatal stage. CFC is characterized by failure to thrive, growth retardation, congenital heart defects,

including HCM and septal defects, dermatologic abnormalities, such as pigmented lesions and hemangiomas, ectodermal abnormalities, including hyperkeratotic skin, neurocognitive delay, seizures and gastrointestinal dysfunction.²⁸ CFC can be caused by activating, heterozygous mutations in *KRAS*, *BRAF*, *MAP2K1* and *MAP2K2*.²⁹

Craniofacial features of CFC include relative macrocephaly, which is usually associated with high cranial vault and forehead, bitemporal narrowing, hypoplastic supraorbital ridges, hypertelorism appearance, short nose with depressed nasal bridge and wide nasal tip, and low-set posteriorly rotated ears (Figure 2E,F). Intraoral findings of CFC include high-arched palate, anterior open bite and posterior crossbite³⁰ (Figure 3E,F).

1.6 | Neurofibromatosis type 1-like syndrome (NFLS or Legius Syndrome)

NFLS (OMIM 611431) is an autosomal dominant disorder that overlaps phenotypically with NF1; however, NFLS is less severe. NFLS is caused by inactivating mutations in *SPRED1*.³¹ The prevalence of Legius syndrome is not known; however, studies show that nearly 2% of NF1 individuals have *SPRED1* mutations.³² Individuals with NFLS typically have multiple café-au-lait spots, sometimes associated with skin fold freckling, lipomas and mild learning disabilities; however, NFLS individuals do not present with neurofibromas, optic gliomas, Lisch nodules or MPNSTs observed in NF1. Craniofacial features of NFLS include macrocephaly and hypertelorism.³³

1.7 | Capillary malformation-arteriovenous malformation syndrome (CM-AVM)

CM-AVM (OMIM 163000) is an autosomal dominant disorder caused by mutations in *RASA1* characterized by capillary malformations (CMs) that may be associated with high flow lesions, arteriovenous malformations (AVMs) and arteriovenous fistulas (AVFs).³⁴ These CMs, AVMs and AVFs are multifocal and can be cutaneous, subcutaneous, intramuscular or intraosseous and can also appear in various internal organs, including the heart and brain. The prevalence of CM-AVM is not known.

CM-AVMs can be present on the face (forehead, lip and/or nose) and/or neck. In the craniofacial region, CM-AVMs may cause soft tissue hypertrophy, and intraosseous AVMs in the maxilla or mandible may cause occlusal distortion, tooth mobility and gingival bleeding.³⁵

2 | DISCUSSION

Here, we reviewed the reported craniofacial and dental findings of the most common RASopathies. Although the analysis of dental findings of the RASopathies in the literature is limited, oral features may prove useful in diagnosis. For example, CFC and NSML are similar syndromes, and while a distinguishing feature of NSML is the development of lentiginosities, these may not present until 4-5 years of age,

making early diagnosis difficult. From the limited case reports available, missing teeth in both primary and permanent dentition have been noted in NSML but not CFC individuals. Thus, tooth number could provide a diagnostic feature to differentiate NSML from CFC. However, much work is necessary to carefully delineate the oral and dental findings in large cohorts of individuals with the RASopathies in order to use these features as diagnostic criteria.

In addition, characterization of intraoral features of the RASopathies can help dentists and orthodontists treat these individuals. NS, CS and CFC individuals should be monitored for development of malocclusion and referred to an orthodontist at the appropriate time, possibly in early mixed dentition to treat crossbite and class III malocclusion. However, additional clinical studies are necessary to provide clear treatment guidelines.

Finally, the RASopathies may be used as genetic models to understand malocclusion. For example, analysing the malocclusion in a particular RASopathy, such as class III malocclusion in CS, and correlating the phenotype to the causative gene, *HRAS* in this case, may begin to further elucidate the genetics underlying malocclusion. Once we understand more fully the genes involved in specific malocclusions, we may modulate these genes and the proteins they encode to treat patients in a more precise method, thus advancing the goal of personalized orthodontics.

ACKNOWLEDGEMENTS

Financial support for this work was provided by funding from the Chinese Scholarship Council (H.C.), K12-DE023574 and AAOF PFA (A.F.G.) and R35-DE026602 (O.D.K).

CONFLICT OF INTEREST

No conflict of interest to declare.

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How to cite this article: Cao H, Alrejaye N, Klein OD, Goodwin AF, Oberoi S. A review of craniofacial and dental findings of the RASopathies. *Orthod Craniofac Res.* 2017; 20(Suppl. 1):32–38. <https://doi.org/10.1111/ocr.12144>