**Name of journal: World Journal of Medical Genetics**

**ESPS Manuscript NO: 6923**

**Columns: Minireviews**

**Osteopathia striata with cranial sclerosis, Wilms tumor, and the *WTX* gene**

Cattaneo E *et al.* OSCS, WT, and *WTX*

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**Supported by** Associazione Bianca Garavaglia, 21052 Busto Arsizio, Varese, Italy; Italian Association for Cancer Research (AIRC); Fondazione Pierfranco e Luisa Mariani, 20129 Milano, Italy

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**Received:** October 29, 2013 **Revised:** [February](http://www.iciba.com/February) 10, 2014

**Accepted: February 16, 2014**

**Published online:**

**Abstract**

Osteopathia striata with cranial sclerosis (OSCS, OMIM#300373) is an X-linked dominant sclerosing bone dysplasia that shows a distinct phenotype in females and males. In 2009, Zandra Jenkins and colleagues found that germline mutations in the FAM123B/WTX/AMER1 gene, mapped to chromosome Xq11.2, cause both the familial and sporadic forms of OSCS. Intriguingly, the *WTX* gene was already known as a putative tumor suppressor gene, since in 2007 Miguel Rivera and colleagues had reported inactivating *WTX* mutations in Wilms tumor (WT), the most frequent renal tumor of childhood. Here we review the heterogeneous clinical presentation of OSCS patients and the involvement of *WTX* anomalies in OSCS and in WT.

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**Key words**: OSCS; Wilms tumor; WTX; Mutation; Genetics

**Core tip:** Osteopathia striata with cranial sclerosis (OSCS), a condition often benign in females and severe and lethal in males, has a clinically heterogeneous presentation. Germline anomalies affecting the *WTX* gene, mapped to chromosome X, are causative of OSCS. Despite *WTX* mutations in Wilms tumor (WT) closely mirror those identified in OSCS patients, individuals with OSCS do not develop WT. This is in contrast with other syndromic conditions, in which constitutional mutations or epimutations, also found as somatic events in sporadic WTs, predispose to WT development.

Cattaneo E, Ciceri S, Liberati N, Radice P, Tarani L, Selicorni A, Perotti D. Osteopathia striata with cranial sclerosis, Wilms tumor, and the *WTX* gene

**Available from:**

**DOI:**

**OSTEOPATHIA STRIATA WITH CRANIAL SCLEROSIS**

The X-linked inheritance pattern of osteopathia striata with cranial sclerosis (OSCS, OMIM#300373), previously predicted on clinical grounds, found confirmation when germline mutations involving the *WTX* gene, mapped to chromosome Xq11.2, were identified as the cause of OSCS[1]. All mutations either deleted the entire gene or resulted in the premature termination of translation[1].

The FAM123B/WTX/AMER1 gene encodes a 1135-amino acid protein characterized by multiple protein-protein interaction domains and N-terminal phosphatidylinositol 4,5-bisphosphate binding domains that mediate its localization to the plasma membrane[1–3]. The WTX protein has been demonstrated to regulate the stability of β-catenin[2], a key control point of the WNT/β-catenin signaling pathway (reviewed in Clevers and Nusse 2012[4]). The critical importance of this pathway during embryogenesis is clearly demonstrated by the pleiotropic clinical presentation of OSCS patients. The *WTX* gene has two splice forms, WTXs1 full length, and WTXs2, a shorter form encoding a 858-amino acid protein that lacks residues 50-326 and does not localize to the plasma membrane[1,5]. Only WTXs1 is considered to be important in regulating the WNT signaling in the context of the development, since disease-causing *WTX* mutations that do not affect the integrity of WTXs2 have been reported[1,6–8].

Females affected with OSCS present a great variability of the phenotype, and, while different studies suggested a nonrandom X-inactivation[9–11] that could explain this phenomenon[6], Jenkins *et al*[1] demonstrated that in 19 *WTX* mutation-bearing heterozygous females X-inactivation ratios were not skewed.

Among the features that constitute the OSCS female phenotype, sclerosis of bone (especially the increased thickness and density mostly of the cranial base) and the fine, uniform, linear striations of the tubular bones are considered the hallmarks of the disease.

Cranial sclerosis is the most typical and early feature, being present since birth. It appears before the longitudinal striae that become evident in the first years of life. Fan-like striations of the iliac bones are present in more than 50% of cases. It is worth mentioning that longitudinal striations at the metaphyses and diaphyses of the tubular bones are seen only in females and in males that are mosaic for a *WTX* mutation[6,7,9,12].

Other skeletal defects reported in the literature, although quite rare, are thoracic (pectus excavatum, broad flat ribs) and vertebral anomalies (2%), digital flection contractures, phalangeal duplication, syndactyly, short or absent fibula and club feet (3%)[12]. Coronal craniostenosis has been described in one patient only[9].

Facial dysmorphisms are rather frequent and sometimes the only pathological feature in addition to the sclerosis of the skull and the longitudinal striation of the long bones. Macrocephaly is documented in almost half of the patients, followed by frontal and occipital bossing, prominent forehead, maxillary hypoplasia, mandible overgrowth with protuberance of the jaw and dental malocclusion. Female patients can also manifest ocular hypertelorism, downslanting palpebral fissures, broad and depressed nasal bridge, narrow high arched palate, and low set dysplastic ears[13–22]. Dental anomalies have been reported in 30% of the patients[20]. Regarding the neurological manifestations, intellectual disability has been described in a small percentage of patients, mainly associated with central nervous system defects (ventricular dilatation, abnormal gyration, corpus callosum hypoplasia or agenesis, hydrocephalus), as well as developmental and speech delay.

Conductive hearing loss can be considered as a distinctive symptom of the disease, occurring in almost 50% of the patients. In the remaining half, hearing loss is sensorineural or of mixed type[6,7,12,20,23]. Deafness is the result of bone sclerosis of mastoid cells, narrowing of the middle ear cavity, the mastoid antrum and the Eustachian canal, and of impaired mobility of the ossicles. High resolution computed tomography of the temporal bone has shown the presence in different patients of bilateral thickening and bone sclerosis of the skull base and mastoid cells, and the abnormal ossicular fixation to the bone surface of the middle ear cavity[23]. Sensorineural hearing loss could instead be due to the nerve encroachment.

Other cranial nerve deficiencies (oculomotor and hypoglossal, abducens and maxillary nerves), due to the narrowing of the nerve canals and foramina by the sclerosing process, are reported. Unilateral peripheral facial palsy and congenital facial palsy were described in 4 patients[20,24]. The optic nerve may also be involved, due to the narrowing of the optic foramina. Nerve palsy might be due to the sclerosing bone process[25], but it is also hypothesized that disruption of the nerve supporting vessels may lead to secondary cranial nerve deficiencies[20]. Lumbar spinal stenosis, defined as narrowing of the lumbar spinal canal, nerve root canal or intervertebral foramina, has been described in one patient only and it could be thought as a neurological complication of the disease[26].

As already mentioned, OSCS can manifests only with the hallmarks of the syndrome (cranial sclerosis and longitudinal striations of the long bones) accompanied by minor facial dysmorphisms, or in association with internal organ anomalies, growth and mental retardation.

In female patients, the most frequently affected organs are the heart, with congenital defects including ventricular septal defects, patent ductus arteriosus, pulmonary atresia and valve stenosis, the lungs and the respiratory system in general, and the gastrointestinal and urogenital systems. The respiratory system may be affected in many patients. In particular, laryngotracheomalacia, nasal obstruction and recurrent bronchitis are reported in 13.5% of the patients[12,20]. Cleft palate (Pierre Robin’s triad) and bifid uvula can also be observed.Gastrointestinal anomalies, including omphalocele, intestinal malrotation and Hirschsprung disease have been reported in 12% of the patients[9,27,28]. Anal stenosis has been described in two girls only[29,30].

OSCS in males is more severe than in females because it follows an X-linked dominant pattern of inheritance that determines hemizygosity of the mutation and, consequently, a wide spectrum of severe clinical manifestations, such as abortion, stillbirth and post-natal lethality. Despite of this, cases with long survival are also described, allowing a clinical distinction in severe and mild forms in males. The male severe phenotype exhibits macrocephaly, facial dysmorfisms (frontal bossing, hypertelorism, low set ears, broad depressed nasal bridge, and micrognathia) and bony sclerosis (more marked than in females), with no metaphyseal striations, while other features are less frequent. The latter include genitourinary malformations (18%), bilateral absence of fibula (65%), cardiac defects (patent ductus arteriosus, atrial and ventricular septal defects, left ventricular non-compaction, tricuspid insufficiency, and vascular ring) (31%), omphalocele and cleft of lips and palate (50%), ventriculomegaly and duplicated phalanges (30%)[8,31]. Prominent lumbar lordosis, joint luxation, camptodactyly, and flexion contractures are also present with lower incidence. Gastrointestinal anomalies as omphalocele, duodenal web, malrotation of the gut, inguinal hernia, and Hirschsprung disease have also been reported[9,10,21,27,32].

In the severe form, the prognosis is related to the severity of visceral malformations and a short survival is often present.

The mild phenotype is qualitatively different from the severe one, being characterized by the presence of mild neurodevelopmental delay (50% of patients), which might be attributable to the relative longevity of these patients, and progressive neuromuscular disease, histologically similar to nemaline myopathy[8], and by the absence of some anomalies as fibular aplasia, duplicated phalanges, syndactily[1,8], and gastrointestinal[9,10,21,27,32], cardiac[9,21,27,31,33,34] and genitourinary malformations[1,8,21,35,36].

Characteristic features of the mild form are short stature, facial dysmorfisms and macrocephaly with cranial sclerosis, frontal bossing, hearing loss, high arched and cleft palate (75%), bifid uvula (25%), and extensive bony sclerosis with absent methaphyseal striations[8]. Milder bony sclerosis has been detected in males with mosaic mutation of *WTX* [37]. Striations of the long bones have also been observed in molecularly confirmed or suspected mosaics for *WTX* mutations[8,24,26,34,37,38].

A possible genotype-phenotype correlation between the position of the *WTX* mutation and survival in males had been initially proposed[1], but further studies showed that this correlation is not absolute[6,7].

**WILMS TUMOR**

Intriguingly, *WTX* has been also identified as a putative tumor suppressor gene in Wilms tumor (WT). Since this gene, as already mentioned, resides on the X chromosome, it has been speculated that its anti-oncogenic activity can be inactivated by a single “hit” both in hemizygous males and in heterozygous females if the mutation affects the only functional allele on the active X chromosome[39]. WT, the most common renal tumor of childhood, is an embryonal malignancy of the kidney that is thought to arise from metanephric mesenchyme. Histologically, it resembles fetal kidney, with varying proportions of blastemal, epithelial and stromal elements[40]. Approximately 40% of WTs occur in association with nephrogenic rests (NRs), embryonal remnants in the kidney which are known precursor lesions for WT[41]. The genetics of WT is heterogeneous and the *WT1* gene at 11p13 and the *WT2* locus at 11p15.5 have been associated with WT pathogenesis (reviewed in Huff 2011[42], Royer-Pokora 2013[43]). Further genes linked to WT development include, in addition to *WTX*, *CTNNB1* and *TP53*[42,43]. *WTX* anomalies have been described in approximately 20% of WTs[39,44–47]: while *WTX* deletions and truncating mutations are somatically acquired, missense mutations, of unknown functional relevance, can be present in the germline (reviewed in Huff 2011[42]).

**OSCS, WT AND *WTX* MUTATIONS, IS THERE AN ASSOCIATION?**

Whole gene deletions represent the majority of *WTX* mutations in WTs, whereas truncating mutations are more common in OSCS. However, the spectrum of *WTX* truncating mutations in OSCS patients and in WTs is very similar[1,42] (Figure 1).

Different syndromic conditions associated with susceptibility to WT, such as the WAGR, the Denys-Drash, and the Beckwith-Wiedemann syndromes, are due to constitutional mutations or epimutations affecting genes/loci also found involved in somatic events in sporadic WTs (reviewed in Scott 2006[48]). In contrast,  individuals with OSCS do not seem to have any predisposition to develop either WT or other malignancies[1,22,35], although in a few of these patients the presence of bilateral multifocal NRs has been reported[8,35]. However, it has to be noted that NRs are found in approximately 1% of infant autopsies and that most of them do not form WT, but spontaneously undergo regression or involution[40]. Thus, the detection of NRs in OSCS patients does not allow establishing a link with WT. Consistently, the *WTX*-knockout mice, despite exhibiting somatic overgrowth and malformation of several organs including kidney, do not appear to be tumor prone[49]. The lack of association between OSCS and WT could be explained assuming that *WTX* is mainly involved in WT progression rather than in its early phase. This possibility is supported by a study detecting various levels of *WTX* mutation in different microdissected areas of the same tumor[46].

Overall, current evidences suggest a possible involvement of the *WTX* gene in kidney development, but are not consistent with its role in WT predisposition.

**REFERENCES**

1 **Jenkins ZA**, van Kogelenberg M, Morgan T, Jeffs A, Fukuzawa R, Pearl E, Thaller C, Hing AV, Porteous ME, Garcia-Miñaur S, Bohring A, Lacombe D, Stewart F, Fiskerstrand T, Bindoff L, Berland S, Adès LC, Tchan M, David A, Wilson LC, Hennekam RC, Donnai D, Mansour S, Cormier-Daire V, Robertson SP. Germline mutations in WTX cause a sclerosing skeletal dysplasia but do not predispose to tumorigenesis. *Nat Genet* 2009; **41**: 95-100 [PMID: 19079258 DOI: 10.1038/ng.270]

2 **Major MB**, Camp ND, Berndt JD, Yi X, Goldenberg SJ, Hubbert C, Biechele TL, Gingras AC, Zheng N, Maccoss MJ, Angers S, Moon RT. Wilms tumor suppressor WTX negatively regulates WNT/beta-catenin signaling. *Science* 2007; **316**: 1043-1046 [PMID: 17510365 DOI: 10.1126/science/1141515]

3 **Grohmann A**, Tanneberger K, Alzner A, Schneikert J, Behrens J. AMER1 regulates the distribution of the tumor suppressor APC between microtubules and the plasma membrane. *J Cell Sci* 2007; **120**: 3738-3747 [PMID: 17925383 DOI: 10.1242/jcs.011320]

4 **Clevers H**, Nusse R. Wnt/β-catenin signaling and disease. *Cell* 2012; **149**: 1192-1205 [PMID: 22682243 DOI: 10.1016/j.cell.2012.05.012]

5 **Rivera MN**, Kim WJ, Wells J, Stone A, Burger A, Coffman EJ, Zhang J, Haber DA. The tumor suppressor WTX shuttles to the nucleus and modulates WT1 activity. *Proc Natl Acad Sci U S A* 2009; **106**: 8338-8343 [PMID: 19416806 DOI: 10.1073/pnas.0811349106]

6 **Perdu B**, de Freitas F, Frints SG, Schouten M, Schrander-Stumpel C, Barbosa M, Pinto-Basto J, Reis-Lima M, de Vernejoul MC, Becker K, Freckmann ML, Keymolen K, Haan E, Savarirayan R, Koenig R, Zabel B, Vanhoenacker FM, Van Hul W. Osteopathia striata with cranial sclerosis owing to WTX gene defect. *J Bone Miner Res* 2010; **25**: 82-90 [PMID: 20209645 DOI: 10.1359/jbmr.090707]

7 **Perdu B**, Lakeman P, Mortier G, Koenig R, Lachmeijer AM, Van Hul W. Two novel WTX mutations underscore the unpredictability of male survival in osteopathia striata with cranial sclerosis. *Clin Genet* 2011; **80**: 383-388 [PMID: 20950377 DOI: 10.1111/j.1399-0004.2010.01553.x]

8 **Holman SK**, Daniel P, Jenkins ZA, Herron RL, Morgan T, Savarirayan R, Chow CW, Bohring A, Mosel A, Lacombe D, Steiner B, Schmitt-Mechelke T, Schroter B, Raas-Rothschild A, Miñaur SG, Porteous M, Parker M, Quarrell O, Tapon D, Cormier-Daire V, Mansour S, Nash R, Bindoff LA, Fiskerstrand T, Robertson SP. The male phenotype in osteopathia striata congenita with cranial sclerosis. *Am J Med Genet A* 2011; **155A**: 2397-2408 [PMID: 22043478]

9 **Viot G**, Lacombe D, David A, Mathieu M, de Broca A, Faivre L, Gigarel N, Munnich A, Lyonnet S, Le Merrer M, Cormier-Daire V. Osteopathia striata cranial sclerosis: non-random X-inactivation suggestive of X-linked dominant inheritance. *Am J Med Genet* 2002; **107**: 1-4 [PMID: 11807859 DOI: 10.1002/ajmg.10028]

10 **Rott HD**, Krieg P, Rütschle H, Kraus C. Multiple malformations in a male and maternal osteopathia strata with cranial sclerosis (OSCS). *Genet Couns* 2003; **14**: 281-288 [PMID: 14577672]

11 **Kraus C**, König R, Rott HD. Comments on "osteopathia striata cranial sclerosis: non-random X-inactivation suggestive of X-linked dominant inheritance". *Am J Med Genet A* 2003; **119A**: 400 [PMID: 12784316 DOI: 10.1002/ajmg.a.20178]

12 **Zicari AM**, Tarani L, Perotti D, Papetti L, Nicita F, Liberati N, Spalice A, Salvatori G, Guaraldi F, Duse M. WTX R353X mutation in a family with osteopathia striata and cranial sclerosis (OS-CS): case report and literature review of the disease clinical, genetic and radiological features. *Ital J Pediatr* 2012; **38**: 27 [PMID: 22716240 DOI: 10.1186/1824-7288-38-27]

13 **Jones MD**, Mulcahy ND. Osteopathia striata, osteopetrosis, and impaired hearing. A case report. *Arch Otolaryngol* 1968; **87**: 116-118 [PMID: 5635349 DOI: 10.1001/archotol.1968.00760060118004]

14 **Franklyn PP**, Wilkinson D. Two cases of osteopathia striata, deafness and cranial osteopetrosis. *Ann Radiol (Paris)* 1978; **21**: 91-93 [PMID: 677756]

15 **Cortina H**, Vallcanera A, Vidal J. Familial osteopathia striata with cranial condensation. *Pediatr Radiol* 1981; **11**: 87-90 [PMID: 7301452 DOI: 10.1007/BF00971786]

16 **Clément A**, Garrigues C, Coursault-Durand R, Ledoux-Lebard G, Bonnin A. [A rare bone disease, but one not to be ignored: osteopathia striata]. *J Radiol* 1982; **63**: 673-676 [PMID: 7153962]

17 **Robinow M**, Unger F. Syndrome of osteopathia striata, macrocephaly, and cranial sclerosis. *Am J Dis Child* 1984; **138**: 821-823 [PMID: 6475869]

18 **Piechowiak H**, Goebel FD, Hirche U, Tyrell R. Cranial sclerosis with striated bone disease (osteopathia striata). *Klin Padiatr* 1986; **198**: 418-424 [PMID: 3784439]

19 **Kornreich L**, Grunebaum M, Ziv N, Shuper A, Mimouni M. Osteopathia striata, cranial sclerosis with cleft palate and facial nerve palsy. *Eur J Pediatr* 1988; **147**: 101-103 [PMID: 3276523 DOI: 10.1007/BF00442625]

20 **König R**, Dukiet C, Dörries A, Zabel B, Fuchs S. Osteopathia striata with cranial sclerosis: variable expressivity in a four generation pedigree. *Am J Med Genet* 1996; **63**: 68-73 [PMID: 8723089 DOI: 10.1002/(SICI)1096-8628(19960503)63: 1<68: : AID-AJMG14>3.0.CO; 2-S]

21 **Pellegrino JE**, McDonald-McGinn DM, Schneider A, Markowitz RI, Zackai EH. Further clinical delineation and increased morbidity in males with osteopathia striata with cranial sclerosis: an X-linked disorder? *Am J Med Genet* 1997; **70**: 159-165 [PMID: 9128936 DOI: 10.1002/(SICI)1096-8628(19970516)70: 2<159: : AID-AJMG11>3.3.CO; 2-C]

22 **Behninger C**, Rott HD. Osteopathia striata with cranial sclerosis: literature reappraisal argues for X-linked inheritance. *Genet Couns* 2000; **11**: 157-167 [PMID: 10893667]

23 **Magliulo G**, Parrotto D, Zicari AM, Zappala D, Lo Mele L, Primicerio P, Marini M. Osteopathia striata-cranial sclerosis: otorhinolaryngologic clinical presentation and radiologic findings. *Am J Otolaryngol* 2007; **28**: 59-63 [PMID: 17162136 DOI: 10.1016/j.amjoto.2006.05.003]

24 **Ciceri S**, Cattaneo E, Fossati C, Radice P, Selicorni A, Perotti D. First evidence of vertical paternal transmission of osteopatia striata with cranial sclerosis. *Am J Med Genet A* 2013; **161A**: 1173-1176 [PMID: 23494899 DOI: 10.1002/ajmg.a.35813]

25 **De Keyser J**, Bruyland M, De Greve J, Leemans J, Potvliege R, Six R, Ebinger G. Osteopathia striata with cranial sclerosis. Report of a case and review of the literature. *Clin Neurol Neurosurg* 1983; **85**: 41-48 [PMID: 6303664 DOI: 10.1016/0303-8467(83)90022-7]

26 **Deniz FE**, Köseoğlu RD. Osteopathia striata with cranial sclerosis and lumbar spinal stenosis. *Acta Neurochir (Wien)* 2007; **149**: 811-85; discussion 815 [PMID: 17558457 DOI: 10.1007/s00701-007-1182-5]

27 **Bar-Oz B**, Mogle P, Ben-Neriah Z, Sheffer R, Arad I. Duodenal web in the syndrome of osteopathia striata with cranial sclerosis. *Clin Genet* 1996; **49**: 329-330 [PMID: 8884088 DOI: 10.1111/j.1399-0004.1996.tb03802.x]

28 **Koudstaal MJ**, Wolvius EB, Ongkosuwito EM, van der Wal KG. Surgically assisted rapid maxillary expansion in two cases of osteopathia striata with cranial sclerosis. *Cleft Palate Craniofac J* 2008; **45**: 337-342 [PMID: 18452358 DOI: 10.1597/07-016]

29 **Savarirayan R**, Nance J, Morris L, Haan E, Couper R. Osteopathia striata with cranial sclerosis: highly variable phenotypic expression within a family. *Clin Genet* 1997; **52**: 199-205 [PMID: 9383023 DOI: 10.1111/j.1399-0004.1997.tb02547.x]

30 **Ward LM**, Rauch F, Travers R, Roy M, Montes J, Chabot G, Glorieux FH. Osteopathia striata with cranial sclerosis: clinical, radiological, and bone histological findings in an adolescent girl. *Am J Med Genet A* 2004; **129A**: 8-12 [PMID: 15266607 DOI: 10.1002/ajmg.a.30107]

31 **Currarino G**, Friedman JM. Severe craniofacial sclerosis with multiple anomalies in a boy and his mother. *Pediatr Radiol* 1986; **16**: 441-447 [PMID: 3774390 DOI: 10.1007/BF02387953]

32 **Keymolen K**, Bonduelle M, De Maeseneer M, Liebaers I. How to counsel in osteopathia striata with cranial sclerosis. *Genet Couns* 1997; **8**: 207-211 [PMID: 9327263]

33 **Bueno AL**, Ramos FJ, Bueno O, Olivares JL, Bello ML, Bueno M. Severe malformations in males from families with osteopathia striata with cranial sclerosis. *Clin Genet* 1998; **54**: 400-405 [PMID: 9842992]

34 **Lüerssen K**, Ptok M. Osteopathia striata with cranial sclerosis and hearing loss. *Eur Arch Otorhinolaryngol* 2006; **263**: 123-126 [PMID: 16010569 DOI: 10.1007/s00405-005-0972-8]

35 **Fukuzawa R**, Holman SK, Chow CW, Savarirayan R, Reeve AE, Robertson SP. WTX mutations can occur both early and late in the pathogenesis of Wilms tumour. *J Med Genet* 2010; **47**: 791-794 [PMID: 20679664 DOI: 10.1136/jmg.2010.080663]

36 **Murphy-Ryan M**, Kirmani S, Thompson DM, Binkovitz LA, Thomas KB, Babovic-Vuksanovic D. A novel sclerosing skeletal dysplasia with mixed sclerosing bone dysplasia, characteristic syndromic features, and clinical and radiographic evidence of male-male transmission. *Am J Med Genet A* 2012; **158A**: 2292-2296 [PMID: 22821701 DOI: 10.1002/ajmg.a.35497]

37 **Chénier S**, Noor A, Dupuis L, Stavropoulos DJ, Mendoza-Londono R. Osteopathia striata with cranial sclerosis and developmental delay in a male with a mosaic deletion in chromosome region Xq11.2. *Am J Med Genet A* 2012; **158A**: 2946-2952 [PMID: 22987541 DOI: 10.1002/ajmg.a.35619]

38 **Joseph DJ**, Ichikawa S, Econs MJ. Mosaicism in osteopathia striata with cranial sclerosis. *J Clin Endocrinol Metab* 2010; **95**: 1506-1507 [PMID: 20150574 DOI: 10.1210/jc.2009-2343]

39 **Rivera MN**, Kim WJ, Wells J, Driscoll DR, Brannigan BW, Han M, Kim JC, Feinberg AP, Gerald WL, Vargas SO, Chin L, Iafrate AJ, Bell DW, Haber DA. An X chromosome gene, WTX, is commonly inactivated in Wilms tumor. *Science* 2007; **315**: 642-645 [PMID: 17204608 DOI: 10.1055/s-2008-1033900]

40 **Beckwith JB**. Nephrogenic rests and the pathogenesis of Wilms tumor: developmental and clinical considerations. *Am J Med Genet* 1998; **79**: 268-273 [PMID: 9781906 DOI: 10.1002/(SICI)1096-8628]

41 **Beckwith JB**, Kiviat NB, Bonadio JF. Nephrogenic rests, nephroblastomatosis, and the pathogenesis of Wilms' tumor. *Pediatr Pathol* 1990; **10**: 1-36 [PMID: 2156243 DOI: 10.3109/15513819009067094]

42 **Huff V**. Wilms' tumours: about tumour suppressor genes, an oncogene and a chameleon gene. *Nat Rev Cancer* 2011; **11**: 111-121 [PMID: 21248786 DOI: 10.1038/nrc3002]

43 **Royer-Pokora B**. Genetics of pediatric renal tumors. *Pediatr Nephrol* 2013; **28**: 13-23 [PMID: 22461142 DOI: 10.1007/s00467-012-2146-4]

44 **Ruteshouser EC**, Robinson SM, Huff V. Wilms tumor genetics: mutations in WT1, WTX, and CTNNB1 account for only about one-third of tumors. *Genes Chromosomes Cancer* 2008; **47**: 461-470 [PMID: 18311776 DOI: 10.1002/gcc.20553]

45 **Perotti D**, Gamba B, Sardella M, Spreafico F, Terenziani M, Collini P, Pession A, Nantron M, Fossati-Bellani F, Radice P. Functional inactivation of the WTX gene is not a frequent event in Wilms' tumors. *Oncogene* 2008; **27**: 4625-4632 [PMID: 18391980 DOI: 10.1038/onc.2008.93]

46 **Wegert J**, Wittmann S, Leuschner I, Geissinger E, Graf N, Gessler M. WTX inactivation is a frequent, but late event in Wilms tumors without apparent clinical impact. *Genes Chromosomes Cancer* 2009; **48**: 1102-1111 [PMID: 19760609 DOI: 10.1002/gcc.20712]

47 **Fukuzawa R**, Anaka MR, Weeks RJ, Morison IM, Reeve AE. Canonical WNT signalling determines lineage specificity in Wilms tumour. *Oncogene* 2009; **28**: 1063-1075 [PMID: 19137020 DOI: 10.1038/onc.2008.455]

48 **Scott RH**, Stiller CA, Walker L, Rahman N. Syndromes and constitutional chromosomal abnormalities associated with Wilms tumour. *J Med Genet* 2006; **43**: 705-715 [PMID: 16690728]

49 **Moisan A**, Rivera MN, Lotinun S, Akhavanfard S, Coffman EJ, Cook EB, Stoykova S, Mukherjee S, Schoonmaker JA, Burger A, Kim WJ, Kronenberg HM, Baron R, Haber DA, Bardeesy N. The WTX tumor suppressor regulates mesenchymal progenitor cell fate specification. *Dev Cell* 2011; **20**: 583-596 [PMID: 21571217 DOI: 10.1016/j.devcel.2011.03.013]

**P-Reviewers:** Fukuzawa R, Sangkhathat S **S-Editor:** Song XX **L-Editor: E-Editor:**

**Figure 1 *WTX* mutations in osteopathia striata with cranial sclerosis and Wilms tumor.** The full length WTX protein possesses two phosphatidylinositol(4,5)-bisphosphate (PtdIns(4,5)P2) binding domains, three adenomatous polyposis coli binding domains (APCBD) and a β-catenin binding region (red line). The smaller WTX isoform lacks aminoacids 50-326 (green line). Mutations of known functional importance include whole gene deletions and mutations resulting in truncated protein products. Arrows indicate the position of mutations introducing a stop codon or causing a frameshift of the reading frame and a premature stop codon.