

Tables S1 and S2

[Click here to Download Table S1 and S2](#)

References of tables S1 and S2

- Abramsson, A., Kurup, S., Busse, M., Yamada, S., Lindblom, P., Schallmeiner, E., Stenzel, D., Sauvaget, D., Ledin, J., Ringvall, M. et al.** (2007). Defective N-sulfation of heparan sulfate proteoglycans limits PDGF-BB binding and pericyte recruitment in vascular development. *Genes Dev.* **21**, 316-331.
- Adhikari, N., Basi, D.L., Townsend, D., Rusch, M., Mariash, A., Mullegama, S., Watson, A., Larson, J., Tan, S., Lerman, B. et al.** (2010). Heparan sulfate Ndst1 regulates vascular smooth muscle cell proliferation, vessel size and vascular remodeling. *J. Mol. Cell. Cardiol.* **49**, 287-293.
- Adhikari, N., Billaud, M., Carlson, M., Lake, S.P., Montaniel, K.R., Staggs, R., Guan, W., Walek, D., Desir, S. et al.** (2014). Vascular biomechanical properties in mice with smooth muscle specific deletion of Ndst1. *Mol. Cell. Biochem.* **385**, 225-238.
- Ahn, J., Lüdecke, H.J., Lindow, S., Horton, W.A., Lee, B., Wagner, M.J., Horsthemke, and B., Wells, D.E.** (1995). Cloning of the putative tumour suppressor gene for hereditary multiple exostoses (EXT1). *Nat. Genet.* **11**, 137-143.
- Ai, X., Kitazawa, T., Do, A.T., Kusche-Gullberg, M., Labosky, P.A., and Emerson, C.P. Jr.** (2007). SULF1 and SULF2 regulate heparan sulfate-mediated GDNF signaling for esophageal innervation. *Development* **134**, 3327-3338.
- Aikawa, T., Whipple, C.A., Lopez, M.E., Gunn, J., Young, A., Lander, A.D., and Korc, M.** (2008). Glypican-1 modulates the angiogenic and metastatic potential of human and mouse cancer cells. *J. Clin. Invest.* **118**, 89-99.

- Aikio, M., Hurskainen, M., Brideau, G., Hägg, P., Sormunen, R., Heljasvaara, R., Gould, D.B., and Pihlajaniemi, T.** (2013). Collagen XVIII short isoform is critical for retinal vascularization, and overexpression of the Tsp-1 domain affects eye growth and cataract formation. *Invest. Ophthalmol. Vis. Sci.* **54**, 7450-7462.
- Aikio, M., Elamaa, H., Vicente, D., Izzi, V., Kaur, I., Seppinen, L., Speedy, H.E., Kaminska, D., Kuusisto, S., Sormunen, R. et al.** (2014). Specific collagen XVIII isoforms promote adipose tissue accrual via mechanisms determining adipocyte number and affect fat deposition. *Proc. Natl. Acad. Sci. USA* **111**, E3043-3052.
- Alexander, C.M., Reichsman, F., Hinkes, M.T., Lincecum, J., Becker, K.A., Cumberledge, S., and Bernfield, M.** (2000). Syndecan-1 is required for Wnt-1-induced mammary tumorigenesis in mice. *Nat. Genet.* **25**, 329-332.
- Allen, N.J., Bennett, M.L., Foo, L.C., Wang, G.X., Chakraborty, C., Smith, S.J., and Barres, B.A.** (2012). Astrocyte glycans 4 and 6 promote formation of excitatory synapses via GluA1 AMPA receptors. *Nature* **486**, 410-414.
- Arikawa-Hirasawa, E., Watanabe, H., Takami, H., Hassell, J.R., and Yamada, Y.** (1999). Perlecan is essential for cartilage and cephalic development. *Nat. Genet.* **23**, 354-358.
- Arikawa-Hirasawa, E., Wilcox, W.R., Le, A.H., Silverman, N., Govindraj, P., Hassell, J.R., and Yamada, Y.** (2001). Dyssegmental dysplasia, Silverman-Handmaker type, is caused by functional null mutations of the perlecan gene. *Nat. Genet.* **27**, 431-434.
- Arikawa-Hirasawa, E., Le, A.H., Nishino, I., Nonaka, I., Ho, N.C., Francomano, C.A., Govindraj, P., Hassell, J.R., Devaney, J.M., Spranger, J. et al.** (2002a). Structural and functional mutations of the perlecan gene cause Schwartz-Jampel syndrome, with myotonic myopathy and chondrodysplasia. *Am. J. Hum. Genet.* **70**, 1368-1375.
- Arikawa-Hirasawa, E., Rossi, S.G., Rotundo, R.L., and Yamada, Y.** (2002b). Absence of acetylcholinesterase at the neuromuscular junctions of perlecan-null mice. *Nat. Neurosci.* **5**, 119-123.
- Arking, D.E., Reinier, K., Post, W., Jui, J., Hilton, G., O'Connor, A., Prineas, R.J., Boerwinkle, E., Psaty, B.M., Tomaselli, G.F. et al.** (2010). Genome-wide association study identifies GPC5 as a novel genetic locus protective against sudden cardiac arrest. *PLoS One* **5**, e9879.

- Arrington, C.B. and Yost, H.J.** (2009). Extra-embryonic syndecan 2 regulates organ primordia migration and fibrillogenesis throughout the zebrafish embryo. *Development* **136**, 3143-3152.
- Arrington, C.B., Peterson, A.G., and Yost, H.J.** (2013). Sdc2 and Tbx16 regulate Fgf2-dependent epithelial cell morphogenesis in the ciliated organ of asymmetry. *Development* **140**, 4102-4109.
- Astudillo, P., Carrasco, H., and Larraín, J.** (2014). Syndecan-4 inhibits Wnt/β-catenin signaling through regulation of low-density-lipoprotein receptor-related protein (LRP6) and R-spondin 3. *Int. J. Biochem. Cell Biol.* **46**, 103-112.
- Axelsson, J., Xu, D., Kang, B.N., Nussbacher, J.K., Handel, T.M., Ley, K., Sriramaraao, P., and Esko, J.D.** (2012). Inactivation of heparan sulfate 2-O-sulfotransferase accentuates neutrophil infiltration during acute inflammation in mice. *Blood* **120**, 1742-1751.
- Baker, A.B., Groothuis, A., Jonas, M., Ettenson, D.S., Shazly, T., Zcharia, E., Vlodavsky, I., Seifert, P., and Edelman, E.R.** (2009). Heparanase alters arterial structure, mechanics, and repair following endovascular stenting in mice. *Circ. Res.* **104**, 380-387.
- Banerjee, S., Isaacman-Beck, J., Schneider, V.A., and Granato, M.** (2013). A novel role for Lh3 dependent ECM modifications during neural crest cell migration in zebrafish. *PLoS One* **8**, e54609.
- Baranzini, S.E., Wang, J., Gibson, R.A., Galwey, N., Naegelin, Y., Barkhof, F., Radue, E.W., Lindberg, R.L., Uitdehaag, B.M., Johnson, M.R. et al.** (2009). Genome-wide association analysis of susceptibility and clinical phenotype in multiple sclerosis. *Hum. Mol. Genet.* **18**, 767-778.
- Bertolesi, G.E., Michaiel, G., and McFarlane, S.** (2008). Two heparanase splicing variants with distinct properties are necessary in early Xenopus development. *J. Biol. Chem.* **283**, 16004-16016.
- Bespakov, M.M., Sidorova, Y.A., Tumova, S., Ahonen-Bishopp, A., Magalhães, A.C., Kulesskiy, E., Paveliev, M., Rivera, C., Rauvala, H., and Saarma, M.** (2011). Heparan sulfate proteoglycan syndecan-3 is a novel receptor for GDNF, neurturin, and artemin. *J. Cell Biol.* **192**, 153-169.
- Bink, R.J., Habuchi, H., Lele, Z., Dolk, E., Joore, J., Rauch, G.J., Geisler, R., Wilson, S.W., den Hertog, J., Kimata, K., and Zivkovic, D.** (2003). Heparan sulfate 6-o-sulfotransferase is essential for muscle development in zebrafish. *J. Biol. Chem.* **278**, 31118-31127.

- Bishop, J.R., Passos-Bueno, M.R., Fong, L., Stanford, K.I., Gonzales, J.C., Yeh, E., Young, S.G., Bensadoun, A., Witztum, J.L., Esko, J.D., and Moulton, K.S.** (2010). Deletion of the basement membrane heparan sulfate proteoglycan type XVIII collagen causes hypertriglyceridemia in mice and humans. *PLoS One* **5**, e13919.
- Bode, L., Salvestrini, C., Park, P.W., Li, J.P., Esko, J.D., Yamaguchi, Y., Murch, S., and Freeze, H.H.** (2008). Heparan sulfate and syndecan-1 are essential in maintaining murine and human intestinal epithelial barrier function. *J. Clin. Invest.* **118**, 229-238.
- Bogdanik, L.P. and Burgess, R.W.** (2011). A valid mouse model of AGRIN-associated congenital myasthenic syndrome. *Hum. Mol. Genet.* **20**, 4617-4633.
- Bullock, S.L., Fletcher, J.M., Beddington, R.S., and Wilson, V.A.** (1998). Renal agenesis in mice homozygous for a gene trap mutation in the gene encoding heparan sulfate 2-sulfotransferase. *Genes Dev.* **12**, 1894-1906.
- Burgess, R.W., Nguyen, Q.T., Son, Y.J., Lichtman, J.W., and Sanes, J.R.** (1999). Alternatively spliced isoforms of nerve- and muscle-derived agrin: their roles at the neuromuscular junction. *Neuron* **23**, 33-44.
- Bush, K.T., Crawford, B.E., Garner, O.B., Nigam, K.B., Esko, J.D., and Nigam, S.K.** (2012). N-sulfation of heparan sulfate regulates early branching events in the developing mammary gland. *J. Biol. Chem.* **287**, 42064-42070.
- Cadwalader, E.L., Condic, M.L., and Yost, H.J.** (2012). 2-O-sulfotransferase regulates Wnt signaling, cell adhesion and cell cycle during zebrafish epiboly. *Development* **139**, 1296-1305.
- Cai, Z., Grobe, K., and Zhang, X.** (2014). Role of heparan sulfate proteoglycans in optic disc and stalk morphogenesis. *Dev. Dyn.* **243**, 1310-1316.
- Campos-Xavier, A.B., Martinet, D., Bateman, J., Belluocchio, D., Rowley, L., Tan, T.Y., Baxová, A., Gustavson, K.H., Borochowitz, Z.U., Innes, A.M. et al.** (2009). Mutations in the heparan-sulfate proteoglycan glypcan 6 (GPC6) impair endochondral ossification and cause recessive omodysplasia. *Am. J. Hum. Genet.* **84**, 760-770.
- Cano-Gauci, D.F., Song, H.H., Yang, H., McKerlie, C., Choo, B., Shi, W., Pullano, R., Piscione, T.D., Grisaru, S., Soon, S. et al.** (1999). Glypican-3-deficient mice exhibit developmental

overgrowth and some of the abnormalities typical of Simpson-Golabi-Behmel syndrome. *J. Cell. Biol.* **146**, 255-264.

Capurro, M.I., Xu, P., Shi, W., Li, F., Jia, A., and Filmus, J. (2008). Glypican-3 inhibits Hedgehog signaling during development by competing with patched for Hedgehog binding. *Dev. Cell* **14**, 700-711.

Capurro, M.I., Li, F., and Filmus, J. (2009). Overgrowth of a mouse model of Simpson-Golabi-Behmel syndrome is partly mediated by Indian hedgehog. *EMBO Rep.* **10**, 901-907.

Cénit, M.D., Blanco-Kelly, F., de las Heras, V., Bartolomé, M., de la Concha, E.G., Urcelay, E., Arroyo, R., and Martínez, A. (2009). Glypican 5 is an interferon-beta response gene: a replication study. *Mult. Scler.* **15**, 913-917.

Chand, A.L., Robertson, D.M., Shelling, A.N., and Harrison, C.A. (2007). Mutational analysis of betaglycan/TGF-betaRIII in premature ovarian failure. *Fertil. Steril.* **87**, 210-212.

Chen, E., Hermanson, S., and Ekker, S.C. (2004). Syndecan-2 is essential for angiogenic sprouting during zebrafish development. *Blood* **103**, 1710-1719.

Chen, E., Stringer, S.E., Rusch, M.A., Selleck, S.B., and Ekker, S.C. (2005). A unique role for 6-O sulfation modification in zebrafish vascular development. *Dev. Biol.* **284**, 364-376.

Chen, J., Repunte-Canonigo, V., Kawamura, T., Lefebvre, C., Shin, W., Howell, L.L., Hemby, S.E., Harvey, B.K., Califano, A., Morales, M. et al. (2013). Hypothalamic proteoglycan syndecan-3 is a novel cocaine addiction resilience factor. *Nat. Commun.* **4**, 1955.

Chen, S., Wassenhove-McCarthy, D.J., Yamaguchi, Y., Holzman, L.B., van Kuppevelt, T.H., Jenniskens, G.J., Wijnhoven, T.J., Woods, A.C., and McCarthy, K.J. (2008). Loss of heparan sulfate glycosaminoglycan assembly in podocytes does not lead to proteinuria. *Kidney Int.* **74**, 289-299.

Clegg, J.M., Conway, C.D., Howe, K.M., Price, D.J., Mason, J.O., Turnbull, J.E., Basson, M.A., and Pratt, T. (2014) Heparan sulfotransferases Hs6st1 and Hs2st keep Erk in check for mouse corpus callosum development. *J. Neurosci.* **34**, 2389-2401.

- Clément, A., Wiweger, M., von der Hardt, S., Rusch, M.A., Selleck, S.B., Chien, C.B., and Roehl, H.H.** (2008). Regulation of zebrafish skeletogenesis by ext2/dackel and papst1/pinscher. *PLoS Genet.* **4**, e1000136.
- Compton, L.A., Potash, D.A., Brown, C.B., and Barnett, J.V.** (2007). Coronary vessel development is dependent on the type III transforming growth factor beta receptor. *Circ Res.* **101**, 784-791.
- Conway, C.D., Howe, K.M., Nettleton, N.K., Price, D.J., Mason, J.O., and Pratt, T.** (2001). Heparan sulfate sugar modifications mediate the functions of slits and other factors needed for mouse forebrain commissure development. *J. Neurosci.* **31**, 1955-1970.
- Conway, C.D., Price, D.J., Pratt, T., and Mason, J.O.** (2011). Analysis of axon guidance defects at the optic chiasm in heparan sulphate sulphotransferase compound mutant mice. *J. Anat.* **219**, 734-742.
- Cornelison, D.D., Wilcox-Adelman, S.A., Goetinck, P.F., Rauvala, H., Rapraeger, A.C., and Olwin, B.B.** (2004). Essential and separable roles for Syndecan-3 and Syndecan-4 in skeletal muscle development and regeneration. *Genes Dev.* **18**, 2231-2236.
- Costell, M., Carmona, R., Gustafsson, E., González-Iriarte, M., Fässler, R., and Muñoz-Chápuli, R.** (2002). Hyperplastic conotruncal endocardial cushions and transposition of great arteries in perlecan-null mice. *Circ. Res.* **91**, 158-164.
- Cottereau, E., Mortemousque, I., Moizard, M.P., Bürglen, L., Lacombe, D., Gilbert-Dussardier, B., Sigaudy, S., Boute, O., David, A., Faivre, L. et al.** (2013). Phenotypic spectrum of Simpson-Golabi-Behmel syndrome in a series of 42 cases with a mutation in GPC3 and review of the literature. *Am. J. Med. Genet. C. Semin. Med. Genet.* **163C**, 92-105.
- Coulson-Thomas, V.J., Gesteira, T.F., Esko, J., and Kao, W.** (2014). Heparan sulfate regulates hair follicle and sebaceous gland morphogenesis and homeostasis. *J. Biol. Chem.* **289**, 25211-25226.
- Crawford, B.E., Garner, O.B., Bishop, J.R., Zhang, D.Y., Bush, K.T., Nigam, S.K., and Esko, J.D.** (2010). Loss of the heparan sulfate sulfotransferase, Ndst1, in mammary epithelial cells selectively blocks lobuloalveolar development in mice. *PLoS One* **5**, e10691.

- Cui, S., Leyva-Vega, M., Tsai, E.A., EauClaire, S.F., Glessner, J.T., Hakonarson, H., Devoto, M., Haber, B.A., Spinner, N.B., and Matthews, R.P.** (2013). Evidence from human and zebrafish that GPC1 is a biliary atresia susceptibility gene. *Gastroenterology* **144**, 1107-1115.
- Daly, S.B., Urquhart, J.E., Hilton, E., McKenzie, E.A., Kammerer, R.A., Lewis, M., Kerr, B., Stuart, H., Donnai, D., Long, D.A. et al.** (2010). Mutations in HPSE2 cause urofacial syndrome. *Am. J. Hum. Genet.* **86**, 963-969.
- De Cat, B., Muyldeermans, S.Y., Coomans, C., Degeest, G., Vanderschueren, B., Creemers, J., Biemar, F., Peers, B., and David, G.** (2003). Processing by proprotein convertases is required for glypcan-3 modulation of cell survival, Wnt signaling, and gastrulation movements. *J. Cell Biol.* **163**, 625-635.
- Dedkov, E.I., Thomas, M.T., Sonka, M., Yang, F., Chittenden, T.W., Rhodes, J.M., Simons, M., Ritman, E.L., and Tomanek, R.J.** (2007). Synectin/syndecan-4 regulate coronary arteriolar growth during development. *Dev. Dyn.* **236**, 2004-2010.
- Dhamija, R., Graham, J.M. Jr., Smaoui, N., Thorland, E., and Kirmani, S.** (2014). Novel de novo SPOCK1 mutation in a proband with developmental delay, microcephaly and agenesis of corpus callosum. *Eur. J. Med. Genet.* **57**, 181-184.
- Dixit, H., Rao, K.L., Padmalatha, V.V., Kanakavalli, M., Deenadayal, M., Gupta, N., Chakrabarty, B.N., and Singh, L.** (2006). Mutational analysis of the betaglycan gene-coding region in susceptibility for ovarian failure. *Hum. Reprod.* **21**, 2041-2046.
- Duchez, S., Pascal, V., Cogné, N., Jayat-Vignoles, C., Julien, R., and Cogné, M.** (2011). Glycotranscriptome study reveals an enzymatic switch modulating glycosaminoglycan synthesis during B-cell development and activation. *Eur. J. Immunol.* **41**, 3632-3644.
- Echaniz-Laguna, A., Rene, F., Marcel, C., Bangratz, M., Fontaine, B., Loeffler, J.P., and Nicole, S.** (2009). Electrophysiological studies in a mouse model of Schwartz-Jampel syndrome demonstrate muscle fiber hyperactivity of peripheral nerve origin. *Muscle Nerve* **40**, 55-61.
- Echtermeyer, F., Streit, M., Wilcox-Adelman, S., Saoncella, S., Denhez, F., Detmar, M., and Goetinck, P.** (2001). Delayed wound repair and impaired angiogenesis in mice lacking syndecan-4. *J. Clin. Invest.* **107**, R9-R14.

- Elamaa, H., Sormunen, R., Rehn, M., Soininen, R., and Pihlajaniemi, T.** (2005). Endostatin overexpression specifically in the lens and skin leads to cataract and ultrastructural alterations in basement membranes. *Am J Pathol.* **166**, 221-229.
- Elliott, L., Ashley-Koch, A.E., De Castro, L., Jonassaint, J., Price, J., Ataga, K.I., Levesque, M.C., Brice Weinberg, J., Eckman, J.R., Orringer, E.P. et al.** (2007). Genetic polymorphisms associated with priapism in sickle cell disease. *Br. J. Haematol.* **137**, 262-267.
- Escobedo, N., Contreras, O., Muñoz, R., Farías, M., Carrasco, H., Hill, C., Tran, U., Pryor, S.E., Wessely, O., Copp, A.J., and Larraín, J.** (2013). Syndecan 4 interacts genetically with Vangl2 to regulate neural tube closure and planar cell polarity. *Development* **140**, 3008-3017.
- Fan, G., Xiao, L., Cheng, L., Wang, X., Sun, B., and Hu, G.** (2000). Targeted disruption of NDST-1 gene leads to pulmonary hypoplasia and neonatal respiratory distress in mice. *FEBS Lett.* **467**, 7-11.
- Fellgett, S.W., Maguire, R.J., and Pownall, M.E.** (2015). Sulf1 has ligand dependent effects on canonical and non-canonical Wnt signalling. *J. Cell Sci.* pii: jcs.164467.
- Filipek-Górniok, B., Carlsson, P., Haitina, T., Habicher, J., Ledin, J., and Kjellén, L.** (2015). The ndst gene family in zebrafish: role of ndst1b in pharyngeal arch formation. *PLoS One* **10**, e0119040.
- Fischer, S., Filipek-Gorniok, B., and Ledin J.** (2011). Zebrafish Ext2 is necessary for Fgf and Wnt signaling, but not for Hh signaling. *BMC Dev. Biol.* 2011 Sep 5, 11:53.
- Floer, M., Götte, M., Wild, M.K., Heidemann, J., Gassar, E.S., Domschke, W., Kiesel, L., Luegering, A., and Kucharzik, T.** (2010). Enoxaparin improves the course of dextran sodium sulfate-induced colitis in syndecan-1-deficient mice. *Am. J. Pathol.* **176**, 146-157.
- Forsberg, E., Pejler, G., Ringvall, M., Lunderius, C., Tomasini-Johansson, B., Kusche-Gullberg, M., Eriksson, I., Ledin, J., Hellman, L., and Kjellén, L.** (1999). Abnormal mast cells in mice deficient in a heparin-synthesizing enzyme. *Nature* **400**, 773-776.
- Freeman, S.D., Moore, W.M., Guiral, E.C., Holme, A.D., Turnbull, J.E., and Pownall, M.E.** (2008). Extracellular regulation of developmental cell signaling by XtSulf1. *Dev. Biol.* **320**, 436-445.

- Fuerst, P.G., Rauch, S.M., and Burgess, R.W.** (2007). Defects in eye development in transgenic mice overexpressing the heparan sulfate proteoglycan agrin. *Dev. Biol.* **303**, 165-180.
- Fukai, N., Eklund, L., Marneros, A.G., Oh, S.P., Keene, D.R., Tamarkin, L., Niemelä, M., Ilves, M., Li, E., Pihlajaniemi, T., and Olsen, B.R.** (2002). Lack of collagen XVIII/endostatin results in eye abnormalities. *EMBO J.* **21**, 1535-1544.
- Fuster, M.M., Wang, L., Castagnola, J., Sikora, L., Reddi, K., Lee, P.H., Radek, K.A., Schuksz, M., Bishop, J.R., Gallo, R.L. et al.** (2007). Genetic alteration of endothelial heparan sulfate selectively inhibits tumor angiogenesis. *J. Cell. Biol.* **177**, 539-549.
- Galli, A., Roure, A., Zeller, R., and Dono, R.** (2003). Glypican 4 modulates FGF signalling and regulates dorsoventral forebrain patterning in Xenopus embryos. *Development* **130**, 4919-4929.
- Garner, O.B., Yamaguchi, Y., Esko, J.D., and Videm, V.** (2008). Small changes in lymphocyte development and activation in mice through tissue-specific alteration of heparan sulphate. *Immunology* **125**, 420-429.
- Garner, O.B., Bush, K.T., Nigam, K.B., Yamaguchi, Y., Xu, D., Esko, J.D., and Nigam, S.K.** (2011). Stage-dependent regulation of mammary ductal branching by heparan sulfate and HGF-cMet signaling. *Dev. Biol.* **355**, 394-403.
- Gautam, M., Noakes, P.G., Moscoso, L., Rupp, F., Scheller, R.H., Merlie, J.P., and Sanes, J.R.** (1996). Defective neuromuscular synaptogenesis in agrin-deficient mutant mice. *Cell* **85**, 525-535.
- Gautam, M., DeChiara, T.M., Glass, D.J., Yancopoulos, G.D., and Sanes, J.R.** (1999). Distinct phenotypes of mutant mice lacking agrin, MuSK, or rapsyn. *Brain Res. Dev. Brain Res.* **114**, 171-178.
- Ge, X.N., Ha, S.G., Rao, A., Greenberg, Y.G., Rushdi, M.N., Esko, J.D., Rao, S.P., and Sriramaraao, P.** (2014). Endothelial and leukocyte heparan sulfates regulate the development of allergen-induced airway remodeling in a mouse model. *Glycobiology* **24**, 715-727.
- Ghiselli, G. and Farber, S.A.** (2005). D-glucuronyl C5-epimerase acts in dorso-ventral axis formation in zebrafish. *BMC Dev. Biol.* **12**, 5-19.

- Gil, N., Goldberg, R., Neuman, T., Garsen, M., Zcharia, E., Rubinstein, A.M., van Kuppevelt, T., Meirovitz, A., Pisano, C., Li, J.P. et al.** (2012). Heparanase is essential for the development of diabetic nephropathy in mice. *Diabetes* **61**, 208-216.
- Girós, A., Morante, J., Gil-Sanz, C., Fairén, A., and Costell, M.** (2007). Perlecan controls neurogenesis in the developing telencephalon. *BMC Dev. Biol.* **5**, 7-29.
- Godfrey, E.W., Roe, J., and Heathcote, R.D.** (1999). Overexpression of agrin isoforms in Xenopus embryos alters the distribution of synaptic acetylcholine receptors during development of the neuromuscular junction. *Dev. Biol.* **205**, 22-32.
- Gorsi, B., Liu, F., Ma, X., Chico, T.J., Shrinivasan, A., Kramer, K.L., Bridges, E., Monteiro, R., Harris, A.L., Patient, R., and Stringer, S.E.** (2014). The heparan sulfate editing enzyme Sulf1 plays a novel role in zebrafish VegfA mediated arterial venous identity. *Angiogenesis* **17**, 77-91.
- Gotha, L., Lim, S.Y., Osherov, A.B., Wolff, R., Qiang, B., Erlich, I., Nili, N., Pillarisetti, S., Chang, Y.T., Tran, P.K. et al.** (2014). Heparan sulfate side chains have a critical role in the inhibitory effects of perlecan on vascular smooth muscle cell response to arterial injury. *Am. J. Physiol. Heart. Circ. Physiol.* **307**, H337-345.
- Götte, M., Joussen, A.M., Klein, C., Andre, P., Wagner, D.D., Hinkes, M.T., Kirchhof, B., Adamis, A.P., and Bernfield, M.** (2002). Role of syndecan-1 in leukocyte-endothelial interactions in the ocular vasculature. *Invest. Ophthalmol. Vis. Sci.* **43**, 1135-1141.
- Grandel, H., Draper, B.W., and Schulte-Merker, S.** (2000). dackel acts in the ectoderm of the zebrafish pectoral fin bud to maintain AER signaling. *Development* **127**, 4169-4178.
- Grisaru, S., Cano-Gauci, D., Tee, J., Filmus, J., and Rosenblum, N.D.** (2001). Glypican-3 modulates BMP- and FGF-mediated effects during renal branching morphogenesis. *Dev. Biol.* **231**, 31-46.
- Grobe, K. and Esko, J.D.** (2002). Regulated translation of heparan sulfate N-acetylglicosamine N-deacetylase/n-sulfotransferase isozymes by structured 5'-untranslated regions and internal ribosome entry sites. *J. Biol. Chem.* **277**, 30699-30706.
- Grobe, K., Inatani, M., Pallerla, S.R., Castagnola, J., Yamaguchi, Y., and Esko, J.D.** (2005). Cerebral hypoplasia and craniofacial defects in mice lacking heparan sulfate Ndst1 gene function. *Development* **132**, 3777-3786.

- Ha, E., Kim, M.J., Choi, B.K., Rho, J.J., Oh, D.J., Rho, T.H., Kim, K.H., Lee, H.J., Shin, D.H., and Yim, S.V.** (2006). Positive association of obesity with single nucleotide polymorphisms of syndecan 3 in the Korean population. *J. Clin. Endocrinol. Metab.* **91**, 5095-5099.
- Habuchi, H., Nagai, N., Sugaya, N., Atsumi, F., Stevens, R.L., and Kimata, K.** (2007). Mice deficient in heparan sulfate 6-O-sulfotransferase-1 exhibit defective heparan sulfate biosynthesis, abnormal placentation, and late embryonic lethality. *J. Biol. Chem.* **282**, 15578-15588.
- HajMohammadi, S., Enjyoji, K., Princivalle, M., Christi, P., Lech, M., Beeler, D., Rayburn, H., Schwartz, J.J., Barzegar, S., de Agostini, A.I. et al.** (2003). Normal levels of anticoagulant heparan sulfate are not essential for normal hemostasis. *J. Clin. Invest.* **111**, 989-999.
- Hanai, J., Gloy, J., Karumanchi, S.A., Kale, S., Tang, J., Hu, G., Chan, B., Ramchandran, R., Jha, V., Sukhatme, V.P., and Sokol, S.** (2002). Endostatin is a potential inhibitor of Wnt signaling. *J. Cell Biol.* **158**, 529-539.
- Harfouche, R., Hentschel, D.M., Piecewicz, S., Basu, S., Print, C., Eavarone, D., Kiziltepe, T., Sasisekharan, R., and Sengupta, S.** (2009). Glycome and transcriptome regulation of vasculogenesis. *Circulation* **120**, 1883-1892.
- Hart, M., Li, L., Tokunaga, T., Lindsey, J.R., Hassell, J.R., Snow, A.D., and Fukuchi, K.** (2001). Overproduction of perlecan core protein in cultured cells and transgenic mice. *J. Pathol.* **194**, 262-269.
- Hartmann, U., Hülsmann, H., Seul, J., Röll, S., Midani, H., Breloy, I., Hechler, D., Müller, R., and Paulsson, M.** (2013). Testican-3: a brain-specific proteoglycan member of the BM-40/SPARC/osteonectin family. *J. Neurochem.* **125**, 399-409.
- Hartwig, S., Hu, M.C., Cella, C., Piscione, T., Filmus, J., and Rosenblum, N.D.** (2005). Glypican-3 modulates inhibitory Bmp2-Smad signaling to control renal development in vivo. *Mech. Dev.* **122**, 928-938.
- Hausser, H.J., Ruegg, M.A., Brenner, R.E., and Ksiazek, I.** (2007). Agrin is highly expressed by chondrocytes and is required for normal growth. *Histochem. Cell. Biol.* **127**, 363-374.
- Hayano, S., Kurosaka, H., Yanagita, T., Kalus, I., Milz, F., Ishihara, Y., Islam, M.N., Kawanabe, N., Saito, M., Kamioka, H. et al.** (2012). Roles of heparan sulfate sulfation in dentinogenesis. *J. Biol. Chem.* **287**, 12217-12229.

- Hayashida, K., Chen, Y., Bartlett, A.H., and Park, P.W.** (2008). Syndecan-1 is an in vivo suppressor of Gram-positive toxic shock. *J. Biol. Chem.* **283**, 19895-19903.
- Hienola, A., Tumova, S., Kulesskiy, E., and Rauvala, H.** (2006). N-syndecan deficiency impairs neural migration in brain. *J. Cell. Biol.* **174**, 569-580.
- Hilgenberg, L.G., Ho, K.D., Lee, D., O'Dowd, D.K., and Smith, M.A.** (2002). Agrin regulates neuronal responses to excitatory neurotransmitters in vitro and in vivo. *Mol. Cell. Neurosci.* **19**, 97-110.
- Hilton, M.J., Gutiérrez, L., Martinez, D.A., and Wells, D.E.** (2005). EXT1 regulates chondrocyte proliferation and differentiation during endochondral bone development. *Bone* **36**, 379-386.
- Holmborn, K., Habicher, J., Kasza, Z., Eriksson, A.S., Filipek-Gorniok, B., Gopal, S., Couchman, J.R., Ahlberg, P.E., Wiweger, M., Spillmann, D. et al.** (2012). On the roles and regulation of chondroitin sulfate and heparan sulfate in zebrafish pharyngeal cartilage morphogenesis. *J. Biol. Chem.* **287**, 33905-33916.
- Hu, Z., Yu, M., and Hu, G.** (2007). NDST-1 modulates BMPR and PTHrP signaling during endochondral bone formation in a gene knockout model. *Bone* **40**, 1462-1474.
- Hu, Z., Wang, C., Xiao, Y., Sheng, N., Chen, Y., Xu, Y., Zhang, L., Mo, W., Jing, N., and Hu, G.** (2009). NDST1-dependent heparan sulfate regulates BMP signaling and internalization in lung development. *J. Cell Sci.* **122**, 1145-1154.
- Huegel, J., Mundy, C., Sgariglia, F., Nygren, P., Billings, P.C., Yamaguchi, Y., Koyama, E., and Pacifici, M.** (2013). Perichondrium phenotype and border function are regulated by Ext1 and heparan sulfate in developing long bones: a mechanism likely deranged in Hereditary Multiple Exostoses. *Dev. Biol.* **377**, 100-112.
- Huzé, C., Bauché, S., Richard, P., Chevessier, F., Goillot, E., Gaudon, K., Ben Ammar, A., Chaboud, A., Grosjean, I., Lecuyer, H.A. et al.** (2009). Identification of an agrin mutation that causes congenital myasthenia and affects synapse function. *Am. J. Hum. Genet.* **85**, 155-167.
- Ida-Yonemochi, H., Satokata, I., Ohshima, H., Sato, T., Yokoyama, M., Yamada, Y., and Saku, T.** (2011). Morphogenetic roles of perlecan in the tooth enamel organ: an analysis of overexpression using transgenic mice. *Matrix Biol.* **30**, 379-388.

- Inatani, M., Irie, F., Plump, A.S., Tessier-Lavigne, M., and Yamaguchi, Y.** (2003). Mammalian brain morphogenesis and midline axon guidance require heparan sulfate. *Science* **302**, 1044-1046.
- Inomata, T., Ebihara, N., Funaki, T., Matsuda, A., Watanabe, Y., Ning, L., Xu, Z., Murakami, A., and Arikawa-Hirasawa, E.** (2012). Perlecan-deficient mutation impairs corneal epithelial structure. *Invest. Ophthalmol. Vis. Sci.* **53**, 1277-1284.
- Irie, F., Badie-Mahdavi, H., and Yamaguchi, Y.** (2012). Autism-like socio-communicative deficits and stereotypies in mice lacking heparan sulfate. *Proc. Natl. Acad. Sci. USA* **109**, 5052-5056.
- Ishiguro, K., Kadomatsu, K., Kojima, T., Muramatsu, H., Tsuzuki, S., Nakamura, E., Kusugami, K., Saito, H., and Muramatsu, T.** (2000a). Syndecan-4 deficiency impairs focal adhesion formation only under restricted conditions. *J. Biol. Chem.* **275**, 5249-5252.
- Ishiguro, K., Kadomatsu, K., Kojima, T., Muramatsu, H., Nakamura, E., Ito, M., Nagasaka, T., Kobayashi, H., Kusugami, K., Saito, H., and Muramatsu, T.** (2000b). Syndecan-4 deficiency impairs the fetal vessels in the placental labyrinth. *Dev. Dyn.* **219**, 539-544.
- Ishiguro, K., Kadomatsu, K., Kojima, T., Muramatsu, H., Matsuo, S., Kusugami, K., Saito, H., and Muramatsu, T.** (2001a). Syndecan-4 deficiency increases susceptibility to kappa-carrageenan-induced renal damage. *Lab. Invest.* **81**, 509-516.
- Ishiguro, K., Kadomatsu, K., Kojima, T., Muramatsu, H., Iwase, M., Yoshikai, Y., Yanada, M., Yamamoto, K., Matsushita, T., Nishimura, M. et al.** (2001b). Syndecan-4 deficiency leads to high mortality of lipopolysaccharide-injected mice. *J. Biol. Chem.* **276**, 47483-47488.
- Ishijima, M., Suzuki, N., Hozumi, K., Matsunobu, T., Kosaki, K., Kaneko, H., Hassell, J.R., Arikawa-Hirasawa, E., and Yamada, Y.** (2012). Perlecan modulates VEGF signaling and is essential for vascularization in endochondral bone formation. *Matrix Biol.* **31**, 234-245.
- Iwabuchi, T. and Goetinck, P.F.** (2006). Syndecan-4 dependent FGF stimulation of mouse vibrissae growth. *Mech. Dev.* **123**, 831-841.
- Iwao, K., Inatani, M., Matsumoto, Y., Ogata-Iwao, M., Takihara, Y., Irie, F., Yamaguchi, Y., Okinami, S., and Tanihara, H.** (2009). Heparan sulfate deficiency leads to Peters anomaly in mice by disturbing neural crest TGF-beta2 signaling. *J. Clin. Invest.* **119**, 1997-2008.

- Iwao, K., Inatani, M., Ogata-Iwao, M., Yamaguchi, Y., Okinami, S., and Tanihara, H.** (2010). Heparan sulfate deficiency in periocular mesenchyme causes microphthalmia and ciliary body dysgenesis. *Exp. Eye Res.* **90**, 81-88.
- Izvolsky, K.I., Lu, J., Martin, G., Albrecht, K.H., and Cardoso, W.V.** (2008). Systemic inactivation of Hs6st1 in mice is associated with late postnatal mortality without major defects in organogenesis. *Genesis* **46**, 8-18.
- Jen, Y.H., Musacchio, M., and Lander, A.D.** (2009). Glypican-1 controls brain size through regulation of fibroblast growth factor signaling in early neurogenesis. *Neural Dev.* **4**, 4:33.
- Jia, J., Maccarana, M., Zhang, X., Bespalov, M., Lindahl, U., and Li, J.P.** (2009). Lack of L-iduronic acid in heparan sulfate affects interaction with growth factors and cell signaling. *J. Biol. Chem.* **284**, 15942-15950.
- Jiang, D., Liang, J., Campanella, G.S., Guo, R., Yu, S., Xie, T., Liu, N., Jung, Y., Homer, R., Meltzer, E.B. et al.** (2010). Inhibition of pulmonary fibrosis in mice by CXCL10 requires glycosaminoglycan binding and syndecan-4. *J. Clin. Invest.* **120**, 2049-2057.
- Jones, K.B., Piombo, V., Searby, C., Kurriger, G., Yang, B., Grabelius, F., Roughley, P.J., Morcuende, J.A., Buckwalter, J.A., Capecchi, M.R. et al.** (2010). A mouse model of osteochondromagenesis from clonal inactivation of Ext1 in chondrocytes. *Proc. Natl. Acad. Sci. USA* **107**, 2054-2059.
- Kaksonen, M., Pavlov, I., Võikar, V., Lauri, S.E., Hienola, A., Riekki, R., Lakso, M., Taira, T., and Rauvala, H.** (2002). Syndecan-3-deficient mice exhibit enhanced LTP and impaired hippocampus-dependent memory. *Mol. Cell. Neurosci.* **21**, 158-172.
- Kalus, I., Salmen, B., Viebahn, C., von Figura, K., Schmitz, D., D'Hooge, R., and Dierks, T.** (2009). Differential involvement of the extracellular 6-O-endosulfatases Sulf1 and Sulf2 in brain development and neuronal and behavioural plasticity. *J. Cell. Mol. Med.* **13**, 4505-4521.
- Kaneko, H., Ishijima, M., Futami, I., Tomikawa-Ichikawa, N., Kosaki, K., Sadatsuki, R., Yamada, Y., Kurosawa, H., Kaneko, K., and Arikawa-Hirasawa, E.** (2013). Synovial perlecan is required for osteophyte formation in knee osteoarthritis. *Matrix Biol.* **32**, 178-187.

- Karlsson-Lindahl, L., Schmidt, L., Haage, D., Hansson, C., Taube, M., Egecioglu, E., Tan, Y.X., Admyre, T., Jansson, J.O., Vlodavsky, I, et al.** (2012). Heparanase affects food intake and regulates energy balance in mice. *PLoS One* **7**, e34313.
- Karlstrom, R.O., Trowe, T., Klostermann, S., Baier, H., Brand, M., Crawford, A.D., Grunewald, B., Haffter, P., Hoffmann, H., Meyer, S.U. et al.** (1996). Zebrafish mutations affecting retinotectal axon pathfinding. *Development*. **123**, 427-438.
- Kasza, I., Suh, Y., Wollny, D., Clark, R.J., Roopra, A., Colman, R.J., MacDougald, O.A., Shedd, T.A., Nelson, D.W., Yen, M.I. et al.** (2014). Syndecan-1 is required to maintain intradermal fat and prevent cold stress. *PLoS Genet.* **10**, e1004514.
- Kehoe, O., Kalia, N., King, S., Eustace, A., Boyes, C., Reizes, O., Williams, A., Patterson, A., and Middleton, J.** (2014). Syndecan-3 is selectively pro-inflammatory in the joint and contributes to antigen-induced arthritis in mice. *Arthritis Res. Ther.* **16**, R148.
- Keren, B., Suzuki, O.T., Gérard-Blanluet, M., Brémont-Gignac, D., Elmaleh, M., Titomanlio, L., Delezoide, A.L., Passos-Bueno, M.R., and Verloes, A.** (2007). CNS malformations in Knobloch syndrome with splice mutation in COL18A1 gene. *Am. J. Med. Genet. A*. **143A**, 1514-1518.
- Kerever, A., Mercier, F., Nonaka, R., de Vega, S., Oda, Y., Zalc, B., Okada, Y., Hattori, N., Yamada, Y., and Arikawa-Hirasawa, E.** (2014). Perlecan is required for FGF-2 signaling in the neural stem cell niche. *Stem Cell Res.* **12**, 492-505.
- Kim, M.J., Liu, I.H., Song, Y., Lee, J.A., Halfter, W., Balice-Gordon, R.J., Linney, E., and Cole, G.J.** (2007). Agrin is required for posterior development and motor axon outgrowth and branching in embryonic zebrafish. *Glycobiology* **17**, 231-247.
- Kinnunen, A.I., Sormunen, R., Elamaa, H., Seppinen, L., Miller, R.T., Ninomiya, Y., Janmey, P.A., and Pihlajaniemi, T.** (2011). Lack of collagen XVIII long isoforms affects kidney podocytes, whereas the short form is needed in the proximal tubular basement membrane. *J. Biol. Chem.* **286**, 7755-7764.
- Kobayashi, T., Habuchi, H., Tamura, K., Ide, H., and Kimata, K.** (2007). Essential role of heparan sulfate 2-O-sulfotransferase in chick limb bud patterning and development. *J. Biol. Chem.* **282**, 19589-19597.

- Kobayashi, T., Habuchi, H., Nogami, K., Ashikari-Hada, S., Tamura, K., Ide, H., and Kimata, K.** (2010). Functional analysis of chick heparan sulfate 6-O-sulfotransferases in limb bud development. *Dev. Growth Differ.* **52**, 146-156.
- Kon, S., Ikesue, M., Kimura, C., Aoki, M., Nakayama, Y., Saito, Y., Kurotaki, D., Diao, H., Matsui, Y., Segawa, T. et al.** (2008). Syndecan-4 protects against osteopontin-mediated acute hepatic injury by masking functional domains of osteopontin. *J Exp. Med.* **205**, 25-33.
- Kramer, K.L. and Yost, H.J.** (2002a). Ectodermal syndecan-2 mediates left-right axis formation in migrating mesoderm as a cell-nonautonomous Vg1 cofactor. *Dev. Cell* **2**, 115-124.
- Kramer, K.L., Barnette, J.E., and Yost, H.J.** (2002b). PKCgamma regulates syndecan-2 inside-out signaling during xenopus left-right development. *Cell* **111**, 981-990.
- Ksiazek, I., Burkhardt, C., Lin, S., Seddik, R., Maj, M., Bezakova, G., Jucker, M., Arber, S., Caroni, P., Sanes, J.R. et al.** (2007). Synapse loss in cortex of agrin-deficient mice after genetic rescue of perinatal death. *J. Neurosci.* **27**, 7183-7195.
- Kuriyama, S. and Mayor, R.** (2009). A role for Syndecan-4 in neural induction involving ERK- and PKC-dependent pathways. *Development* **136**, 575-584.
- Lamanna, W.C., Baldwin, R.J., Padva, M., Kalus, I., Ten Dam, G., van Kuppevelt, T.H., Gallagher, J.T., von Figura, K., Dierks, T., and Merry, C.L.** (2006). Heparan sulfate 6-O-endosulfatases: discrete in vivo activities and functional co-operativity. *Biochem. J.* **400**, 63-73.
- LeClair, E.E., Mui, S.R., Huang, A., Topczewska, J.M., and Topczewski, J.** (2009). Craniofacial skeletal defects of adult zebrafish Glypican 4 (knypek) mutants. *Dev. Dyn.* **238**, 2550-2563.
- Lee, J.S., von der Hardt, S., Rusch, M.A., Stringer, S.E., Stickney, H.L., Talbot, W.S., Geisler, R., Nüsslein-Volhard, C., Selleck, S.B., Chien, C.B., and Roehl, H.** (2004). Axon sorting in the optic tract requires HSPG synthesis by ext2 (dackel) and extl3 (boxer). *Neuron* **44**, 947-960.
- Lencz, T., Guha, S., Liu, C., Rosenfeld, J., Mukherjee, S., DeRosse, P., John, M., Cheng, L., Zhang, C., Badner, J.A. et al.** (2013). Genome-wide association study implicates NDST3 in schizophrenia and bipolar disorder. *Nat. Commun.* **4**, 2739.

- Li, H., Yamagata, T., Mori, M., and Momoi, M.Y.** (2002). Association of autism in two patients with hereditary multiple exostoses caused by novel deletion mutations of EXT1. *J. Hum. Genet.* **47**, 262-265.
- Li, J., Partovian, C., Li, J., Hampton, T.G., Metais, C., Tkachenko, E., Sellke, F.W., and Simons, M.** (2002). Modulation of microvascular signaling by heparan sulfate matrix: studies in syndecan-4 transgenic mice. *Microvasc. Res.* **64**, 38-46.
- Li, J.P., Gong, F., Hagner-McWhirter, A., Forsberg, E., Abrink, M., Kisilevsky, R., Zhang, X., and Lindahl, U.** (2003). Targeted disruption of a murine glucuronyl C5-epimerase gene results in heparan sulfate lacking L-iduronic acid and in neonatal lethality. *J. Biol. Chem.* **278**, 28363-28366.
- Li, L., Wang, B., Gao, T., Zhang, X., Hao, J.X., Vlodavsky, I., Wiesenfeld-Hallin, Z., Xu, X.J., and Li, J.P.** (2012). Heparanase overexpression reduces carrageenan-induced mechanical and cold hypersensitivity in mice. *Neurosci. Lett.* **511**, 4-7.
- Lin, X., Wei, G., Shi, Z., Dryer, L., Esko, J.D., Wells, D.E., and Matzuk, M.M.** (2000). Disruption of gastrulation and heparan sulfate biosynthesis in EXT1-deficient mice. *Dev. Biol.* **224**, 299-311.
- Liu, B., Bell, A.W., Paranjpe, S., Bowen, W.C., Khillan, J.S., Luo, J.H., Mars, W.M., and Michalopoulos, G.K.** (2010). Suppression of liver regeneration and hepatocyte proliferation in hepatocyte-targeted glycan 3 transgenic mice. *Hepatology* **52**, 1060-1067.
- Liu, I.H., Zhang, C., Kim, M.J., and Cole, G.J.** (2008). Retina development in zebrafish requires the heparan sulfate proteoglycan agrin. *Dev. Neurobiol.* **68**, 877-898.
- Liu, L., Yang, X., Wang, H., Cui, G., Xu, Y., Wang, P., Yuan, G., Wang, X., Ding, H., and Wang, D.W.** (2013). Association between variants of EXT2 and type 2 diabetes: a replication and meta-analysis. *Hum. Genet.* **132**, 139-145.
- Liu, Y., Echtermeyer, F., Thilo, F., Theilmeier, G., Schmidt, A., Schülein, R., Jensen, B.L., Loddenkemper, C., Jankowski, V., Marcussen, N. et al.** (2012). The proteoglycan syndecan 4 regulates transient receptor potential canonical 6 channels via RhoA/Rho-associated protein kinase signaling. *Arterioscler. Thromb. Vasc. Biol.* **32**, 378-385.
- Lowe, D.A., Lepori-Bui, N., Fomin, P.V., Sloofman, L.G., Zhou, X., Farach-Carson, M.C., Wang, L., and Kirn-Safran, C.B.** (2014). Deficiency in perlecan/HSPG2 during bone

- development enhances osteogenesis and decreases quality of adult bone in mice. *Calcif. Tissue Int.* **95**, 29-38.
- Lum, D.H., Tan, J., Rosen, S.D., and Werb, Z.** (2007). Gene trap disruption of the mouse heparan sulfate 6-O-endosulfatase gene, Sulf2. *Mol. Cell. Biol.* **27**, 678-688.
- Maltseva, I., Chan, M., Kalus, I., Dierks, T., and , S.D.** (2013). The SULFs, extracellular sulfatases for heparan sulfate, promote the migration of corneal epithelial cells during wound repair. *PLoS One* **8**, e69642.
- Marneros, A.G. and Olsen, B.R.** (2003). Age-dependent iris abnormalities in collagen XVIII/endostatin deficient mice with similarities to human pigment dispersion syndrome. *Invest. Ophthalmol. Vis. Sci.* **44**, 2367-2372.
- Marneros, A.G., Keene, D.R., Hansen, U., Fukai, N., Moulton, K., Goletz, P.L., Moiseyev, G., Pawlyk, B.S., Halfter, W., and Dong, S.** (2004). Collagen XVIII/endostatin is essential for vision and retinal pigment epithelial function. *EMBO J.* **23**, 89-99.
- Matsui, Y., Ikesue, M., Danzaki, K., Morimoto, J., Sato, M., Tanaka, S., Kojima, T., Tsutsui, H., and Uede, T.** (2011). Syndecan-4 prevents cardiac rupture and dysfunction after myocardial infarction. *Circ. Res.* **108**, 1328-1339.
- Matsumoto, Y., Irie, F., Inatani, M., Tessier-Lavigne, M., and Yamaguchi, Y.** (2007). Netrin-1/DCC signaling in commissural axon guidance requires cell-autonomous expression of heparan sulfate. *J. Neurosci.* **27**, 4342-4350.
- Matsumoto, K., Irie, F., Mackem, S., and Yamaguchi, Y.** (2010). A mouse model of chondrocyte-specific somatic mutation reveals a role for Ext1 loss of heterozygosity in multiple hereditary exostoses. *Proc. Natl. Acad. Sci. USA* **107**, 10932-10937.
- Matthews, H.K., Marchant, L., Carmona-Fontaine, C., Kuriyama, S., Larraín, J., Holt, M.R., Parsons, M., and Mayor, R.** (2008). Directional migration of neural crest cells in vivo is regulated by Syndecan-4/Rac1 and non-canonical Wnt signaling/RhoA. *Development* **135**, 1771-1780.
- McDermott, S.P., Ranheim, E.A., Leatherberry, V.S., Khwaja, S.S., Klos, K.S., and Alexander, C.M.** (2007). Juvenile syndecan-1 null mice are protected from carcinogen-induced tumor development. *Oncogene* **26**, 1407-1416.

McLaughlin, D., Karlsson, F., Tian, N., Pratt, T., Bullock, S.L., Wilson, V.A., Price, D.J., and Mason, J.O. (2003). Specific modification of heparan sulphate is required for normal cerebral cortical development. *Mech. Dev.* **120**, 1481-1488.

Menzel, O., Bekkeheien, R.C., Reymond, A., Fukai, N., Boye, E., Kosztolanyi, G., Aftimos, S., Deutsch, S., Scott, H.S., Olsen, B.R. et al. (2004). Knobloch syndrome: novel mutations in COL18A1, evidence for genetic heterogeneity, and a functionally impaired polymorphism in endostatin. *Hum. Mutat.* **23**, 77-84.

Meyers, J.R., Planamento, J., Ebrom, P., Kruelewitz, N., Wade, E., and Pownall, M.E. (2013). Sulf1 modulates BMP signaling and is required for somite morphogenesis and development of the horizontal myoseptum. *Dev. Biol.* **378**, 107-121.

Mitchell, K.J., Pinson, K.I., Kelly, O.G., Brennan, J., Zupicich, J., Scherz, P., Leighton, P.A., Goodrich, L.V., Lu, X., Avery, B.J. et al. (2001). Functional analysis of secreted and transmembrane proteins critical to mouse development. *Nat. Genet.* **28**, 241-249.

Montaniel, K.R., Billaud, M., Graham, C., Kim, S.K., Carlson, M., Zeng, W., Zeng, O., Pan, W., Isakson, B.E., Hall, J.L., and Adhikari, N. (2012). Smooth muscle specific deletion of Ndst1 leads to decreased vessel luminal area and no change in blood pressure in conscious mice. *J. Cardiovasc. Transl. Res.* **5**, 274-279.

Morimoto, K., Shimizu, T., Furukawa, K., Morio, H., Kurosawa, H., and Shirasawa, T. (2002). Transgenic expression of the EXT2 gene in developing chondrocytes enhances the synthesis of heparan sulfate and bone formation in mice. *Biochem. Biophys. Res. Commun.* **292**, 999-1009.

Morita, H., Yoshimura, A., Inui, K., Ideura, T., Watanabe, H., Wang, L., Soininen, R., and Tryggvason, K. (2005). Heparan sulfate of perlecan is involved in glomerular filtration. *J. Am. Soc. Nephrol.* **16**, 1703-1710.

Mundy, C., Yasuda, T., Kinumatsu, T., Yamaguchi, Y., Iwamoto, M., Enomoto-Iwamoto, M., Koyama, E., and Pacifici, M. (2011). Synovial joint formation requires local Ext1 expression and heparan sulfate production in developing mouse embryo limbs and spine. *Dev. Biol.* **351**, 70-81.

Muñoz, R., Moreno, M., Oliva, C., Orbenes, C., and Larraín, J. (2006). Syndecan-4 regulates non-canonical Wnt signalling and is essential for convergent and extension movements in Xenopus embryos. *Nat. Cell. Biol.* **8**, 492-500.

- Nadanaka, S., Kagiyama, S., and Kitagawa, H.** (2013a). Roles of EXTL2, a member of the EXT family of tumour suppressors, in liver injury and regeneration processes. *Biochem. J.* **454**, 133-145.
- Nadanaka, S., Zhou, S., Kagiyama, S., Shoji, N., Sugahara, K., Sugihara, K., Asano, M., and Kitagawa, H.** (2013b). EXTL2, a member of the EXT family of tumor suppressors, controls glycosaminoglycan biosynthesis in a xylose kinase-dependent manner. *J. Biol. Chem.* **288**, 9321-9333.
- Nagai, N., Habuchi, H., Sugaya, N., Nakamura, M., Imamura, T., Watanabe, H., and Kimata, K.** (2013). Involvement of heparan sulfate 6-O-sulfation in the regulation of energy metabolism and the alteration of thyroid hormone levels in male mice. *Glycobiology* **23**, 980-992.
- Narvid, J., Gorno-Tempini, M.L., Slavotinek, A., Dearmond, S.J., Cha, Y.H., Miller, B.L., and Rankin, K.** (2009). Of brain and bone: the unusual case of Dr. A. *Neurocase* **15**, 190-205.
- Neugebauer, J.M., Cadwallader, A.B., Amack, J.D., Bisgrove, B.W., and Yost, H.J.** (2013). Differential roles for 3-OSTs in the regulation of cilia length and motility. *Development* **140**, 3892-3902.
- Ng, A., Wong, M., Viviano, B., Erlich, J.M., Alba, G., Pfleiderer, C., Jay, P.Y., and Saunders, S.** (2009). Loss of glypcan-3 function causes growth factor-dependent defects in cardiac and coronary vascular development. *Dev. Biol.* **335**, 208-215.
- Nicole, S., Davoine, C.S., Topaloglu, H., Cattolico, L., Barral, D., Beighton, P., Hamida, C.B., Hammouda, H., Cruaud, C., White, P.S. et al.** (2000). Perlecan, the major proteoglycan of basement membranes, is altered in patients with Schwartz-Jampel syndrome (chondrodystrophic myotonia). *Nat. Genet.* **26**, 480-483.
- Norton, W.H., Ledin, J., Grandel, H., and Neumann, C.J.** (2005). HSPG synthesis by zebrafish Ext2 and Extl3 is required for Fgf10 signalling during limb development. *Development* **132**, 4963-4973.
- Ogata-Iwao, M., Inatani, M., Iwao, K., Takihara, Y., Nakaishi-Fukuchi, Y., Irie, F., Sato, S., Furukawa, T., Yamaguchi, Y., and Tanihara, H.** (2011). Heparan sulfate regulates intraretinal axon pathfinding by retinal ganglion cells. *Invest. Ophthalmol. Vis. Sci.* **52**, 6671-6679.

- Ohkawara, B., Yamamoto, T.S., Tada, M., and Ueno, N.** (2003). Role of glycan 4 in the regulation of convergent extension movements during gastrulation in *Xenopus laevis*. *Development* **130**, 2129-2138.
- Okamoto, K., Tokunaga, K., Doi, K., Fujita, T., Suzuki, H., Katoh, T., Watanabe, T., Nishida, N., Mabuchi, A., Takahashi, A. et al.** (2011). Common variation in GPC5 is associated with acquired nephrotic syndrome. *Nat. Genet.* **43**, 459-463.
- Olivares, G.H., Carrasco, H., Aroca, F., Carvallo, L., Segovia, F., and Larraín, J.** (2009). Syndecan-1 regulates BMP signaling and dorso-ventral patterning of the ectoderm during early *Xenopus* development. *Dev. Biol.* **329**, 338-349.
- Ostrovsyky, O., Shimoni, A., Rand, A., Vlodavsky, I., and Nagler, A.** (2010). Genetic variations in the heparanase gene (HPSE) associate with increased risk of GVHD following allogeneic stem cell transplantation: effect of discrepancy between recipients and donors. *Blood* **115**, 2319-2328.
- Otsuki, S., Hanson, S.R., Miyaki, S., Grogan, S.P., Kinoshita, M., Asahara, H., Wong, C.H., and Lotz, M.K.** (2010). Extracellular sulfatases support cartilage homeostasis by regulating BMP and FGF signaling pathways. *Proc. Natl. Acad. Sci. USA* **107**, 10202-10207.
- Paine-Saunders, S., Viviano, B.L., Zupicich, J., Skarnes, W.C., and Saunders, S.** (2000). glycan-3 controls cellular responses to Bmp4 in limb patterning and skeletal development. *Dev. Biol.* **225**, 179-187.
- Pallerla, S.R., Pan, Y., Zhang, X., Esko, J.D., and Grobe, K.** (2007). Heparan sulfate NdSt1 gene function variably regulates multiple signaling pathways during mouse development. *Dev. Dyn.* **236**, 556-563.
- Pallerla, S.R., Lawrence, R., Lewejohann, L., Pan, Y., Fischer, T., Schlomann, U., Zhang, X., Esko, J.D., and Grobe, K.** (2008). Altered heparan sulfate structure in mice with deleted NDST3 gene function. *J. Biol. Chem.* **283**, 16885-16894.
- Pan, Y., Woodbury, A., Esko, J.D., Grobe, K., and Zhang, X.** (2006). Heparan sulfate biosynthetic gene NdSt1 is required for FGF signaling in early lens development. *Development* **133**, 4933-4944.

- Pan, Y., Carbe, C., Powers, A., Zhang, E.E., Esko, J.D., Grobe, K., Feng, G.S., and Zhang, X.** (2008). Bud specific N-sulfation of heparan sulfate regulates Shp2-dependent FGF signaling during lacrimal gland induction. *Development* **135**, 301-310.
- Pan, Y., Carbe, C., Kupich, S., Pickhinke, U., Ohlig, S., Frye, M., Seelige, R., Pallerla, S.R., Moon, A.M., Lawrence, R. et al.** (2014). Heparan sulfate expression in the neural crest is essential for mouse cardiogenesis. *Matrix Biol.* **35**, 253-265.
- Pang, J., Zhang, S., Yang, P., Hawkins-Lee, B., Zhong, J., Zhang, Y., Ochoa, B., Agundez, J.A., Voelckel, M.A., Fisher, R.B. et al.** (2010). Loss-of-function mutations in HPSE2 cause the autosomal recessive urofacial syndrome. *Am. J. Hum. Genet.* **86**, 957-962.
- Pilia, G., Hughes-Benzie, R.M., MacKenzie, A., Baybayan, P., Chen, E.Y., Huber, R., Neri, G., Cao, A., Forabosco, A., and Schlessinger, D.** (1996). Mutations in GPC3, a glycan gene, cause the Simpson-Golabi-Behmel overgrowth syndrome. *Nat. Genet.* **12**, 241-247.
- Planer, D., Metzger, S., Zcharia, E., Wexler, I.D., Vlodavsky, I., and Chajek-Shaul, T.** (2011). Role of heparanase on hepatic uptake of intestinal derived lipoprotein and fatty streak formation in mice. *PLoS One* **6**, e18370.
- Poon, I.K., Goodall, K.J., Phipps, S., Chow, J.D., Pagler, E.B., Andrews, D.M., Conlan, C.L., Ryan, G.F., White, J.A., Wong, M.K. et al.** (2014). Mice deficient in heparanase exhibit impaired dendritic cell migration and reduced airway inflammation. *Eur. J. Immunol.* **44**, 1016-1030.
- Poulain, F.E. and Chien, C.B.** (2013). Proteoglycan-mediated axon degeneration corrects pretarget topographic sorting errors. *Neuron* **78**, 49-56.
- Pratt, T., Conway, C.D., Tian, N.M., Price, D.J., and Mason, J.O.** (2006). Heparan sulphation patterns generated by specific heparan sulfotransferase enzymes direct distinct aspects of retinal axon guidance at the optic chiasm. *J. Neurosci.* **26**, 6911-6923.
- Qi, Q., Menzaghi, C., Smith, S., Liang, L., de Rekeneire, N., Garcia, M.E., Lohman, K.K., Miljkovic, I., Strotmeyer, E.S., and Cummings, S.R.** (2012). Genome-wide association analysis identifies TYW3/CRYZ and NDST4 loci associated with circulating resistin levels. *Hum. Mol. Genet.* **21**, 4774-4780.
- Qiang, B., Lim, S.Y., Lekas, M., Kuliszewski, M.A., Wolff, R., Osherov, A.B., Rudenko, D., Leong-Poi, H., Noyan, H., Husain, M. et al.** (2014). Perlecan heparan sulfate proteoglycan is a

critical determinant of angiogenesis in response to mouse hind-limb ischemia. *Can. J. Cardiol.* **30**, 1444-1451.

Qu, X., Carbe, C., Tao, C., Powers, A., Lawrence, R., van Kuppevelt, T.H., Cardoso, W.V., Grobe, K., Esko, J.D., and Zhang, X. (2011). Lacrimal gland development and Fgf10-Fgfr2b

signaling are controlled by 2-O- and 6-O-sulfated heparan sulfate. *J. Biol. Chem.* **286**, 14435-14444.

Qu, X., Pan, Y., Carbe, C., Powers, A., Grobe, K., and Zhang, X. (2012). Glycosaminoglycan-dependent restriction of FGF diffusion is necessary for lacrimal gland development. *Development* **139**, 2730-2739.

Ramsbottom, S.A., Maguire, R.J., Fellgett, S.W., and Pownall, M.E. (2014). Sulf1 influences the Shh morphogen gradient during the dorsal ventral patterning of the neural tube in *Xenopus tropicalis*. *Dev. Biol.* **391**, 207-218.

Rauch, S.M., Huen, K., Miller, M.C., Chaudry, H., Lau, M., Sanes, J.R., Johanson, C.E., Stopa, E.G., and Burgess, R.W. (2011). Changes in brain β-amyloid deposition and aquaporin 4 levels in response to altered agrin expression in mice. *J. Neuropathol. Exp. Neurol.* **70**, 1124-1137.

Reijmers, R.M., Vondenhoff, M.F., Roozendaal, R., Kuil, A., Li, J.P., Spaargaren, M., Pals, S.T., and Mebius, R.E. (2010). Impaired lymphoid organ development in mice lacking the heparan sulfate modifying enzyme glucuronyl C5-epimerase. *J. Immunol.* **184**, 3656-3664.

Reijmers, R.M., Groen, R.W., Kuil, A., Weijer, K., Kimberley, F.C., Medema, J.P., van Kuppevelt, T.H., Li, J.P., Spaargaren, M., and Pals, S.T. (2011). Disruption of heparan sulfate proteoglycan conformation perturbs B-cell maturation and APRIL-mediated plasma cell survival. *Blood* **117**, 6162-6171.

Reizes, O., Lincecum, J., Wang, Z., Goldberger, O., Huang, L., Kaksonen, M., Ahima, R., Hinkes, M.T., Barsh, G.S., Rauvala, H., and Bernfield, M. (2001). Transgenic expression of syndecan-1 uncovers a physiological control of feeding behavior by syndecan-3. *Cell* **106**, 105-116.

Reizes, O., Benoit, S.C., Strader, A.D., Clegg, D.J., Akunuru, S., and Seeley, R.J. (2003). Syndecan-3 modulates food intake by interacting with the melanocortin/AgRP pathway. *Ann. NY Acad. Sci.* **994**, 66-73.

- Reuter, M.S., Musante, L., Hu, H., Diederich, S., Sticht, H., Ekici, A.B., Uebe, S., Wienker, T.F., Bartsch, O., Zechner, U. et al.** (2014). NDST1 missense mutations in autosomal recessive intellectual disability. *Am. J. Med. Genet. A.* **164A**, 2753-2763.
- Rieubland, C., Jacquemont, S., Mittaz, L., Osterheld, M.C., Vial, Y., Superti-Furga, A., Unger, S., and Bonafé, L.** (2010). Phenotypic and molecular characterization of a novel case of dyssegmental dysplasia, Silverman-Handmaker type. *Eur. J. Med. Genet.* **53**, 294-298.
- Ringvall, M., Ledin, J., Holmborn, K., van Kuppevelt, T., Ellin, F., Eriksson, I., Olofsson, A.M., Kjellen, L., and Forsberg, E.** (2000). Defective heparan sulfate biosynthesis and neonatal lethality in mice lacking N-deacetylase/N-sulfotransferase-1. *J. Biol. Chem.* **275**, 25926-25930.
- Rodgers, K.D., Sasaki, T., Aszodi, A., and Jacenko, O.** (2007). Reduced perlecan in mice results in chondrodysplasia resembling Schwartz-Jampel syndrome. *Hum. Mol. Genet.* **16**, 515-528.
- Röll, S., Seul, J., Paulsson, M., and Hartmann, U.** (2006). Testican-1 is dispensable for mouse development. *Matrix Biol.* **25**, 373-381.
- Rops, A.L., Götte, M., Baselmans, M.H., van den Hoven, M.J., Steenbergen, E.J., Lensen, J.F., Wijnhoven, T.J., Cevikbas, F., van den Heuvel, L.P., van Kuppevelt, T.H. et al.** (2007). Syndecan-1 deficiency aggravates anti-glomerular basement membrane nephritis. *Kidney Int.* **72**, 1204-1215.
- Rossi, M., Morita, H., Sormunen, R., Airenne, S., Kreivi, M., Wang, L., Fukai, N., Olsen, B.R., Tryggvason, K., and Soininen, R.** (2003). Heparan sulfate chains of perlecan are indispensable in the lens capsule but not in the kidney. *EMBO J.* **22**, 236-245.
- Rygh, C.B., Løkka, G., Heljasvaara, R., Taxt, T., Pavlin, T., Sormunen, R., Pihlajaniemi, T., Curry, F.R., Tenstad, O., and Reed, R.K.** (2014). Image-based assessment of microvascular function and structure in collagen XV- and XVIII-deficient mice. *J Physiol.* **592**, 325-336.
- Sakazume, S., Okamoto, N., Yamamoto, T., Kurosawa, K., Numabe, H., Ohashi, Y., Kako, Y., Nagai, T., and Ohashi, H.** (2007). GPC3 mutations in seven patients with Simpson-Golabi-Behmel syndrome. *Am. J. Med. Genet. A.* **143A**, 1703-1707.
- Sakimoto, T., Kim, T.I., Ellenberg, D., Fukai, N., Jain, S., Azar, D.T., and Chang, J.H.** (2008). Collagen XVIII and corneal reinnervation following keratectomy. *FEBS Lett.* **582**, 3674-3680.

- Samson, S.C., Ferrer, T., Jou, C.J., Sachse, F.B., Shankaran, S.S., Shaw, R.M., Chi, N.C., Tristani-Firouzi, M., and Yost, H.J.** (2013). 3-OST-7 regulates BMP-dependent cardiac contraction. *PLoS Biol.* **11**, e1001727.
- Samuel, M.A., Valdez, G., Tapia, J.C., Lichtman, J.W., and Sanes, J.R.** (2012). Agrin and synaptic laminin are required to maintain adult neuromuscular junctions. *PLoS One* **7**, e46663.
- Sarraj, M.A., Escalona, R.M., Umbers, A., Chua, H.K., Small, C., Griswold, M., Loveland, K., Findlay, J.K., and Stenvers, K.L.** (2010). Fetal testis dysgenesis and compromised Leydig cell function in Tgfbr3 (beta glycan) knockout mice. *Biol. Reprod.* **82**, 153-162.
- Scarpellini, A., Huang, L., Burhan, I., Schroeder, N., Funck, M., Johnson, T.S., and Verderio, E.A.** (2014). Syndecan-4 knockout leads to reduced extracellular transglutaminase-2 and protects against tubulointerstitial fibrosis. *J. Am. Soc. Nephrol.* **25**, 1013-1027.
- Schneider, V.A. and Granato, M.** (2006). The myotomal diwanka (lh3) glycosyltransferase and type XVIII collagen are critical for motor growth cone migration. *Neuron* **50**, 683-695.
- Schüring, A.N., Lutz, F., Tüttelmann, F., Gromoll, J., Kiesel, L., and Götte, M.** (2009). Role of syndecan-3 polymorphisms in obesity and female hyperandrogenism. *J. Mol. Med. (Berl.)* **87**, 1241-1250.
- Seppinen, L., Sormunen, R., Soini, Y., Elamaa, H., Heljasvaara, R., and Pihlajaniemi, T.** (2008). Lack of collagen XVIII accelerates cutaneous wound healing, while overexpression of its endostatin domain leads to delayed healing. *Matrix Biol.* **27**, 535-546.
- Serpinskaya, A.S., Feng, G., Sanes, J.R., and Craig, A.M.** (1999). Synapse formation by hippocampal neurons from agrin-deficient mice. *Dev. Biol.* **205**, 65-78.
- Serralbo, O. and Marcelle, C.** (2014). Migrating cells mediate long-range WNT signaling. *Development* **141**, 2057-2063.
- Sertié, A.L., Sossi, V., Camargo, A.A., Zatz, M., Brahe, C., and Passos-Bueno, M.R.** (2000). Collagen XVIII, containing an endogenous inhibitor of angiogenesis and tumor growth, plays a critical role in the maintenance of retinal structure and in neural tube closure (Knobloch syndrome). *Hum. Mol. Genet.* **9**, 2051-2058.

- Sgariglia, F., Candela, M.E., Huegel, J., Jacenko, O., Koyama, E., Yamaguchi, Y., Pacifici, M., and Enomoto-Iwamoto, M.** (2013). Epiphyseal abnormalities, trabecular bone loss and articular chondrocyte hypertrophy develop in the long bones of postnatal Ext1-deficient mice. *Bone* **57**, 220-231.
- Shah, M.M., Sakurai, H., Sweeney, D.E., Gallegos, T.F., Bush, K.T., Esko, J.D., and Nigam, S.K.** (2010). Hs2st mediated kidney mesenchyme induction regulates early ureteric bud branching. *Dev. Biol.* **339**, 354-365.
- Shi, W. and Filmus, J.** (2009). A patient with the Simpson-Golabi-Behmel syndrome displays a loss-of-function point mutation in GPC3 that inhibits the attachment of this proteoglycan to the cell surface. *Am. J. Med. Genet. A* **149A**, 552-554.
- Shiau, C.E., Hu, N., and Bronner-Fraser, M.** (2010). Altering Glypican-1 levels modulates canonical Wnt signaling during trigeminal placode development. *Dev. Biol.* **348**, 107-118.
- Shieh, Y.E., Wells, D.E., and Sater, A.K.** (2014). Zygotic expression of Exostosin1 (Ext1) is required for BMP signaling and establishment of dorsal-ventral pattern in Xenopus. *Int. J. Dev. Biol.* **58**, 27-34.
- Shimo, T., Gentili, C., Iwamoto, M., Wu, C., Koyama, E., and Pacifici, M.** (2004). Indian hedgehog and syndecans-3 coregulate chondrocyte proliferation and function during chick limb skeletogenesis. *Dev. Dyn.* **229**, 607-617.
- Shimokawa, K., Kimura-Yoshida, C., Nagai, N., Mukai, K., Matsubara, K., Watanabe, H., Matsuda, Y., Mochida, K., and Matsuo, I.** (2011). Cell surface heparan sulfate chains regulate local reception of FGF signaling in the mouse embryo. *Dev. Cell* **21**, 257-272.
- Shworak, N.W., HajMohammadi, S., de Agostini, A.I., and Rosenberg, R.D.** (2002). Mice deficient in heparan sulfate 3-O-sulfotransferase-1: normal hemostasis with unexpected perinatal phenotypes. *Glycoconj. J.* **19**, 355-361.
- Sipola, A., Seppinen, L., Pihlajaniemi, T., and Tuukkanen, J.** (2009). Endostatin affects osteoblast behavior in vitro, but collagen XVIII/endostatin is not essential for skeletal development in vivo. *Calcif. Tissue Int.* **85**, 412-420.
- Song, H.H., Shi, W., Xiang, Y.Y., and Filmus, J.** (2005). The loss of glycan-3 induces alterations in Wnt signaling. *J. Biol. Chem.* **280**, 2116-2125.

- Stanford, K.I., Bishop, J.R., Foley, E.M., Gonzales, J.C., Niesman, I.R., Witztum, J.L., and Esko, J.D.** (2009). Syndecan-1 is the primary heparan sulfate proteoglycan mediating hepatic clearance of triglyceride-rich lipoproteins in mice. *J. Clin. Invest.* **119**, 3236-3245.
- Stanford, K.I., Wang, L., Castagnola, J., Song, D., Bishop, J.R., Brown, J.R., Lawrence, R., Bai, X., Habuchi, H., Tanaka, M. et al.** (2010). Heparan sulfate 2-O-sulfotransferase is required for triglyceride-rich lipoprotein clearance. *J. Biol. Chem.* **285**, 286-294.
- Stenvers, K.L., Tursky, M.L., Harder, K.W., Kountouri, N., Amatayakul-Chantler, S., Grail, D., Small, C., Weinberg, R.A., Sizeland, A.M., and Zhu, H.J.** (2003). Heart and liver defects and reduced transforming growth factor beta2 sensitivity in transforming growth factor beta type III receptor-deficient embryos. *Mol. Cell. Biol.* **23**, 4371-4385.
- Stepp, M.A., Gibson, H.E., Gala, P.H., Iglesia, D.D., Pajooohesh-Ganji, A., Pal-Ghosh, S., Brown, M., Aquino, C., Schwartz, A.M., Goldberger, O. et al.** (2002). Defects in keratinocyte activation during wound healing in the syndecan-1-deficient mouse. *J. Cell. Sci.* **115**, 4517-4531.
- Stickens, D., Clines, G., Burbee, D., Ramos, P., Thomas, S., Hogue, D., Hecht, J.T., Lovett, M., and Evans, G.A.** (1996). The EXT2 multiple exostoses gene defines a family of putative tumour suppressor genes. *Nat. Genet.* **14**, 25-32.
- Stickens, D., Zak, B.M., Rougier, N., Esko, J.D., and Werb, Z.** (2005). Mice deficient in Ext2 lack heparan sulfate and develop exostoses. *Development* **132**, 5055-5068.
- Strader, A.D., Reizes, O., Woods, S.C., Benoit, S.C., and Seeley, R.J.** (2004). Mice lacking the syndecan-3 gene are resistant to diet-induced obesity. *J. Clin. Invest.* **114**, 1354-1360.
- Stum, M., Davoine, C.S., Vicart, S., Guillot-Noël, L., Topaloglu, H., Carod-Artal, F.J., Kayserili, H., Hentati, F., Merlini, L., Urtizberea, J.A. et al.** (2006). Spectrum of HSPG2 (Perlecan) mutations in patients with Schwartz-Jampel syndrome. *Hum. Mutat.* **27**, 1082-1091.
- Stum, M., Girard, E., Bangratz, M., Bernard, V., Herbin, M., Vignaud, A., Ferry, A., Davoine, C.S., Echaniz-Laguna, A., René, F. et al.** (2008). Evidence of a dosage effect and a physiological endplate acetylcholinesterase deficiency in the first mouse models mimicking Schwartz-Jampel syndrome neuromyotonia. *Hum. Mol. Genet.* **17**, 3166-3179.
- Sugar, T., Wassenhove-McCarthy, D.J., Esko, J.D., van Kuppevelt, T.H., Holzman, L., and McCarthy, K.J.** (2014). Podocyte-specific deletion of NDST1, a key enzyme in the sulfation of

heparan sulfate glycosaminoglycans, leads to abnormalities in podocyte organization in vivo.

Kidney Int. **85**, 307-318.

Suzuki, O., Kague, E., Bagatini, K., Tu, H., Heljasvaara, R., Carvalhaes, L., Gava, E., de Oliveira, G., Godoi, P., Oliva, G. et al. (2009). Novel pathogenic mutations and skin biopsy analysis in Knobloch syndrome. *Mol. Vis.* **15**, 801-809.

Suzuki, O.T., Sertié, A.L., Der Kaloustian, V.M., Kok, F., Carpenter, M., Murray, J., Czeizel, A.E., Kliemann, S.E., Rosemberg, S., Monteiro, M. et al. (2002). Molecular analysis of collagen XVIII reveals novel mutations, presence of a third isoform, and possible genetic heterogeneity in Knobloch syndrome. *Am. J. Hum. Genet.* **71**, 1320-1329.

Syu, A., Ishiguro, H., Inada, T., Horiuchi, Y., Tanaka, S., Ishikawa, M., Arai, M., Itokawa, M., Niizato, K., Iritani, S. et al. (2010). Association of the HSPG2 gene with neuroleptic-induced tardive dyskinesia. *Neuropsychopharmacology* **35**, 1155-1164.

Takahashi, I., Noguchi, N., Nata, K., Yamada, S., Kaneiwa, T., Mizumoto, S., Ikeda, T., Sugihara, K., Asano, M., Yoshikawa, T. et al. (2009). Important role of heparan sulfate in postnatal islet growth and insulin secretion. *Biochem. Biophys. Res. Commun.* **383**, 113-118.

Tang, G.L. and Weitz, K. (2015). Impaired arteriogenesis in syndecan-1(-/-) mice. *J. Surg. Res.* **193**, 22-27.

Tao, Q., Yokota, C., Puck, H., Kofron, M., Birsoy, B., Yan, D., Asashima, M., Wylie, C.C., Lin, X., and Heasman, J. (2005). Maternal wnt11 activates the canonical wnt signaling pathway required for axis formation in Xenopus embryos. *Cell* **120**, 857-871.

Thompson, W.R., Modla, S., Grindel, B.J., Czymbek, K.J., Kirn-Safran, C.B., Wang, L., Duncan, R.L., and Farach-Carson, M.C. (2011). Perlecan/Hspg2 deficiency alters the pericellular space of the lacunocanalicular system surrounding osteocytic processes in cortical bone. *J. Bone Miner. Res.* **26**, 618-629.

Topczewski, J., Sepich, D.S., Myers, D.C., Walker, C., Amores, A., Lele, Z., Hammerschmidt, M., Postlethwait, J., and Solnica-Krezel, L. (2004). The zebrafish glycan knypek controls cell polarity during gastrulation movements of convergent extension. *Dev. Cell* **1**, 251-264.

Tornberg J., Sykiotis, G.P., Keefe, K., Plummer, L., Hoang, X., Hall, J.E., Quinton, R., Seminara, S.B., Hughes, V., Van Vliet, G. et al. (2011). Heparan sulfate 6-O-sulfotransferase 1, a

- gene involved in extracellular sugar modifications, is mutated in patients with idiopathic hypogonadotropic hypogonadism. *Proc. Natl. Acad. Sci. USA* **108**, 11524-11529.
- Tran, P.K., Tran-Lundmark, K., Soininen, R., Tryggvason, K., Thyberg, J., and Hedin, U.** (2004). Increased intimal hyperplasia and smooth muscle cell proliferation in transgenic mice with heparan sulfate-deficient perlecan. *Circ. Res.* **94**, 550-558.
- Tran, T.H., Shi, X., Zaia, J., and Ai, X.** (2012). Heparan sulfate 6-O-endosulfatases (Sulfs) coordinate the Wnt signaling pathways to regulate myoblast fusion during skeletal muscle regeneration. *J. Biol. Chem.* **287**, 32651-32664.
- Trowe, T., Klostermann, S., Baier, H., Granato, M., Crawford, A.D., Grunewald, B., Hoffmann, H., Karlstrom, R.O., Meyer, S.U., Müller, B. et al.** (1996). Mutations disrupting the ordering and topographic mapping of axons in the retinotectal projection of the zebrafish, *Danio rerio*. *Development* **123**, 439-450.
- Tzeng, S.T., Tsai, M.H., Chen, C.L., Lee, J.X., Jao, T.M., Yu, S.L., Yen, S.J., and Yang, Y.C.** (2013). NDST4 is a novel candidate tumor suppressor gene at chromosome 4q26 and its genetic loss predicts adverse prognosis in colorectal cancer. *PLoS One* **8**, e67040.
- Utriainen, A., Sormunen, R., Kettunen, M., Carvalhaes, L.S., Sajanti, E., Eklund, L., Kauppinen, R., Kitten, G.T., and Pihlajaniemi, T.** (2004). Structurally altered basement membranes and hydrocephalus in a type XVIII collagen deficient mouse line. *Hum. Mol. Genet.* **13**, 2089-2099.
- Venero Galanternik, M., Kramer, K.L., and Piotrowski, T.** (2015). Heparan Sulfate Proteoglycans Regulate Fgf Signaling and Cell Polarity during Collective Cell Migration. *Cell Rep.* pii: S2211-1247(14)01096-1.
- Veugelers, M., Cat, B.D., Muyldermans, S.Y., Reekmans, G., Delande, N., Frints, S., Legius, E., Fryns, J.P., Schrander-Stumpel, C., Weidle, B. et al.** (2000). Mutational analysis of the GPC3/GPC4 glycan gene cluster on Xq26 in patients with Simpson-Golabi-Behmel syndrome: identification of loss-of-function mutations in the GPC3 gene. *Hum. Mol. Genet.* **9**, 1321-1328.
- Viviano, B.L., Silverstein, L., Pfleiderer, C., Paine-Saunders, S., Mills, K., and Saunders, S.** (2005). Altered hematopoiesis in glycan-3-deficient mice results in decreased osteoclast differentiation and a delay in endochondral ossification. *Dev. Biol.* **282**, 152-162.

- Walker, K.A., Sims-Lucas, S., Caruana, G., Cullen-McEwen, L., Li, J., Sarraj, M.A., Bertram, J.F., and Stenvers, K.L.** (2011). Betaglycan is required for the establishment of nephron endowment in the mouse. *PLoS One* **6**, e18723.
- Wang, F., Wolfson, S.N., Gharib, A., and Sagasti, A.** (2012). LAR receptor tyrosine phosphatases and HSPGs guide peripheral sensory axons to the skin. *Curr. Biol.* **22**, 373-382.
- Wang, K.S., Wang, L., Liu, X., and Zeng, M.** (2013). Association of HS6ST3 gene polymorphisms with obesity and triglycerides: gene x gender interaction. *J. Genet.* **92**, 395-402.
- Wang, L., Fuster, M., Sriramarao, P., and Esko, J.D.** (2005). Endothelial heparan sulfate deficiency impairs L-selectin- and chemokine-mediated neutrophil trafficking during inflammatory responses. *Nat. Immunol.* **6**, 902-910.
- Wang, Q., Yang, L., Alexander, C., and Temple, S.** (2012). The niche factor syndecan-1 regulates the maintenance and proliferation of neural progenitor cells during mammalian cortical development. *PLoS One* **7**, e42883.
- Wang, S., Ai, X., Freeman, S.D., Pownall, M.E., Lu, Q., Kessler, D.S., and Emerson, C.P. Jr.** (2004). QSulf1, a heparan sulfate 6-O-endosulfatase, inhibits fibroblast growth factor signaling in mesoderm induction and angiogenesis. *Proc. Natl. Acad. Sci. USA* **101**, 4833-4838.
- Wang, W., Zhong, B., Sun, J., Cao, J., Tian, J., Zhong, N., Zhao, W., Tian, L., Xu, P., Guo, D. et al.** (2011). Down-regulated HS6ST2 in osteoarthritis and Kashin-Beck disease inhibits cell viability and influences expression of the genes relevant to aggrecan metabolism of human chondrocytes. *Rheumatology (Oxford)* **50**, 2176-2186.
- Wei, K.H. and Liu, I.H.** (2014). Heparan sulfate glycosaminoglycans modulate migration and survival in zebrafish primordial germ cells. *Theriogenology* **81**, 1275-1285.
- Wilson, N.H. and Stoeckli, E.T.** (2013). Sonic hedgehog regulates its own receptor on postcrossing commissural axons in a glypican1-dependent manner. *Neuron* **79**, 478-491.
- Wiweger, M.I., Avramut, C.M., de Andrea, C.E., Prins, F.A., Koster, A.J., Ravelli, R.B., and Hogendoorn, P.C.** (2011). Cartilage ultrastructure in proteoglycan-deficient zebrafish mutants brings to light new candidate genes for human skeletal disorders. *J. Pathol.* **223**, 531-542.

- Wiweger, M.I., Zhao, Z., van Merkesteyn, R.J., Roehl, H.H., and Hogendoorn, P.C.** (2012). HSPG-deficient zebrafish uncovers dental aspect of multiple osteochondromas. *PLoS One* **7**, e29734.
- Wuyts, W., Van Hul, W., De Boulle, K., Hendrickx, J., Bakker, E., Vanhoenacker, F., Mollica, F., Lüdecke, H.J., Sayli, B.S., Pazzaglia, U.E. et al.** (1998). Mutations in the EXT1 and EXT2 genes in hereditary multiple exostoses. *Am. J. Hum. Genet.* **62**, 346-354.
- Xiao, T. and Baier, H.** (2007). Lamina-specific axonal projections in the zebrafish tectum require the type IV collagen Dragnet. *Nat. Neurosci.* **10**, 1529-1537.
- Xiong, D.H., Liu, X.G., Guo, Y.F., Tan, L.J., Wang, L., Sha, B.Y., Tang, Z.H., Pan, F., Yang, T.L., Chen, X.D. et al.** (2009). Genome-wide association and follow-up replication studies identified ADAMTS18 and TGFBR3 as bone mass candidate genes in different ethnic groups. *Am. J. Hum. Genet.* **84**, 388-398.
- Xu, J., Park, P.W., Kheradmand, F., and Corry, D.B.** (2005). Endogenous attenuation of allergic lung inflammation by syndecan-1. *J. Immunol.* **174**, 5758-5765.
- Xu, Z., Ichikawa, N., Kosaki, K., Yamada, Y., Sasaki, T., Sakai, L.Y., Kurosawa, H., Hattori, N., and Arikawa-Hirasawa, E.** (2010). Perlecan deficiency causes muscle hypertrophy, a decrease in myostatin expression, and changes in muscle fiber composition. *Matrix Biol.* **29**, 461-470.
- Yamamoto, A., Uchiyama, K., Nara, T., Nishimura, N., Hayasaka, M., Hanaoka, K., and Yamamoto, T.** (2014). Structural abnormalities of corpus callosum and cortical axonal tracts accompanied by decreased anxiety-like behavior and lowered sociability in spock3- mutant mice. *Dev. Neurosci.* **36**, 381-395.
- Yasuda, T., Mundy, C., Kinumatsu, T., Shibukawa, Y., Shibutani, T., Grobe, K., Minugh-Purvis, N., Pacifici, M., and Koyama, E.** (2010). Sulfotransferase Ndst1 is needed for mandibular and TMJ development. *J. Dent. Res.* **89**, 1111-1116.
- Ylikärppä, R., Eklund, L., Sormunen, R., Kontiola, A.I., Utriainen, A., Määttä, M., Fukai, N., Olsen, B.R., and Pihlajaniemi, T.** (2003). Lack of type XVIII collagen results in anterior ocular defects. *FASEB J.* **17**, 2257-2259.

- Zak, B.M., Schuksz, M., Koyama, E., Mundy, C., Wells, D.E., Yamaguchi, Y., Pacifici, M., and Esko, J.D.** (2011). Compound heterozygous loss of Ext1 and Ext2 is sufficient for formation of multiple exostoses in mouse ribs and long bones. *Bone* **48**, 979-987.
- Zcharia, E., Metzger, S., Chajek-Shaul, T., Aingorn, H., Elkin, M., Friedmann, Y., Weinstein, T., Li, J.P., Lindahl, U., Vlodavsky, I.** (2004). Transgenic expression of mammalian heparanase uncovers physiological functions of heparan sulfate in tissue morphogenesis, vascularization, and feeding behavior. *FASEB J.* **18**, 252-263.
- Zcharia, E., Philp, D., Edovitsky, E., Aingorn, H., Metzger, S., Kleinman, H.K., Vlodavsky, I., Elkin, M.** (2005a) Heparanase regulates murine hair growth. *Am. J. Pathol.* **166**, 999-1008.
- Zcharia, E., Zilka, R., Yaar, A., Yacoby-Zeevi, O., Zetser, A., Metzger, S., Sarid, R., Naggi, A., Casu, B., Ilan, N. et al.** (2005b). Heparanase accelerates wound angiogenesis and wound healing in mouse and rat models. *FASEB J.* **19**, 211-221.
- Zcharia, E., Jia, J., Zhang, X., Baraz, L., Lindahl, U., Peretz, T., Vlodavsky, I., Li, J.P.** (2009). Newly generated heparanase knock-out mice unravel co-regulation of heparanase and matrix metalloproteinases. *PLoS One* **4**, e5181.
- Zhang, B., Xiao, W., Qiu, H., Zhang, F., Moniz, H.A., Jaworski, A., Condac, E., Gutierrez-Sanchez, G., Heiss, C., Clugston, R.D. et al.** (2014). Heparan sulfate deficiency disrupts developmental angiogenesis and causes congenital diaphragmatic hernia. *J. Clin. Invest.* **124**, 209-221.
- Zhang, X., Wu, C., Song, J., Götte, M., Sorokin, L.** (2013). Syndecan-1, a cell surface proteoglycan, negatively regulates initial leukocyte recruitment to the brain across the choroid plexus in murine experimental autoimmune encephalomyelitis. *J. Immunol.* **191**, 4551-4556.
- Zhang, Y., Li, J., Partovian, C., Sellke, F.W., Simons, M.** (2003). Syndecan-4 modulates basic fibroblast growth factor 2 signaling in vivo. *Am. J. Physiol. Heart. Circ. Physiol.* **284**, H2078-2082.
- Zheng, Q., Zhu, J., Shanabrough, M., Borok, E., Benoit, S.C., Horvath, T.L., Clegg, D.J., Reizes, O.** (2010). Enhanced anorexigenic signaling in lean obesity resistant syndecan-3 null mice. *Neuroscience* **171**, 1032-1040.
- Zoeller, J.J., McQuillan, A., Whitelock, J., Ho, S.Y., Iozzo, R.V.** (2008). A central function for perlecan in skeletal muscle and cardiovascular development. *J. Cell Biol.* **181**, 381-394.

Zoeller, J.J., Whitelock, J.M., Iozzo, R.V. (2009). Perlecan regulates developmental angiogenesis by modulating the VEGF-VEGFR2 axis. *Matrix Biol.* **28**, 284-291.

Zuberi, R.I., Ge, X.N., Jiang, S., Bahaei, N.S., Kang, B.N., Hosseinkhani, R.M., Frenzel, E.M., Fuster, M.M., Esko, J.D., Rao, S.P., Sriramaraao, P. (2009). Deficiency of endothelial heparan sulfates attenuates allergic airway inflammation. *J. Immunol.* **183**, 3971-3979.