Reviews

Neuroacanthocytosis: Observations, Theories and Perspectives on the Origin and Significance of Acanthocytes

Merel J. W. Adjobo-Hermans¹, Judith C. A. Cluitmans¹ & Giel J. C. G. M. Bosman¹*

¹ Department of Biochemistry, Radboud University Medical Center, Radboud Institute for Molecular Life Sciences, Nijmegen, The Netherlands

Abstract

The presence of acanthocytes in the blood is characteristic of patients suffering from neuroacanthocytosis (NA). Recent studies have described abnormal phosphorylation of the proteins involved in connecting the membrane and cytoskeleton in patient-derived erythrocytes. The involvement of lipids in the underlying signaling pathways and recent reports on in vitro disease-associated lipid alterations support renewed research into lipid composition, signal transduction, and metabolism in patient erythrocytes. In addition to morphology, changes in membrane organization affect erythrocyte function and survival. Patient erythrocytes may have a decreased ability to deform, and this may contribute to accelerated erythrocyte removal and a decreased oxygen supply, especially in vulnerable brain regions. The presently available data indicate that acanthocytes are likely to originate in the bone marrow, making erythropoiesis an obvious new focus in NA research. Moreover, new, detailed morphological observations indicate that acanthocytes may be the tip of the iceberg with regard to misshapen erythrocytes in the circulation of patients with NA.

A systematic assessment of patient erythrocyte morphology, deformability, oxygen delivery, and metabolism will be instrumental in determining the putative contribution of erythrocyte function to NA clinical symptoms.

Keywords: Acanthocytosis, erythrocytes, membrane, neurodegeneration, signaling

Citation: Adjobo-Hermans MJW, Cluitmans JCA, Bosman GJCGM. Neuroacanthocytosis: observations, theories and perspectives on the origin and significance of acanthocytes. Tremor Other Hyperkinet Mov. 2015; 5. doi: 10.7916/D8VH5N2M

* To whom correspondence should be addressed. E-mail: Giel.Bosman@radboudumc.nl

Editor: Ruth Walker, James J. Peters Veterans Affairs Medical Center, Mount Sinai School of Medicine, United States.
Received: May 28, 2015 Accepted: July 31, 2015 Published: August 25, 2015

Copyright: © 2015 Adjobo-Hermans et al. This is an open-access article distributed under the terms of the Creative Commons Attribution–Noncommercial–No Derivatives License, which permits the user to copy, distribute, and transmit the work provided that the original author(s) and source are credited; that no commercial use is made of the work; and that the work is not altered or transformed.

Financial Disclosures: The work of the authors described in this review was financed partly by the Advocacy for Neuroacanthocytosis (G.B.) and the E-RARE programmes EMINA-1 and EMINA-2 (M.A. and J.C.).

Conflict of Interest: The authors report no conflict of interest.

Neuroacanthocytosis: an introduction

Patients suffering from a neuroacanthocytosis (NA) syndrome experience neurological symptoms due to basal ganglia degeneration, and their blood contains acanthocytes with thorn-like protrusions. Genes mutated in patients with chorea-acanthocytosis (ChAc), McLeod syndrome (MLS), and Huntington’s disease-like 2 (HDL-2) have been identified, but neither the functions of the proteins they encode nor the pathophysiologic processes caused by these mutations are well understood. There is also limited knowledge regarding the causes of neurodegeneration with brain iron accumulation (NBIA) such as pantothenate kinase-associated neurodegeneration (PKAN), where the functions of the affected gene products center around lipid modification and metabolism.¹ ² Given the paucity of relevant phenotypes in currently available cellular and animal models, research into the molecular causes of acanthocyte formation and consequences could be performed using easily accessible erythrocytes. This feasible approach could identify mechanisms underlying neurodegenerative processes. Here, we present an inventory of the actual knowledge and current hypotheses, as well as some of our ideas on the most fruitful approaches for unraveling the molecular mechanisms behind acanthocyte formation and subsequent neurodegeneration.

Acanthocyte generation

Acanthocytosis is associated with NA syndromes, but the presence and number of acanthocytes are inconsistent. An overview of the published data suggests that considerable acanthocytosis is associated with MLS, but it is much more variable in ChAc, HDL-2, and PKAN.¹ ² Anecdotal evidence indicates that the fraction of acanthocytes varies in individual patients over time, without a clear association
with clinical symptoms (G. Irvine, personal communication). This seems to exclude the possibility that the transition of possibly susceptible erythrocytes with a normal, discocyte morphology to an acanthocyte is secondary to mechanical stress due to involuntary movements or seizures. This view is supported by the inability to (bio)chemically induce acanthocyte formation in vitro and by the normal deformability of both acanthocytes and discocytes of NA patients in a capillary-mimicking system. In addition, detailed microscopic analyses have shown that methodological aspects cannot be underestimated in distinguishing between acanthocytes and erythrocytes with an acanthocyte-like morphology. The issue remains unresolved given the complexity of clinical symptoms in patients with NA and the likely but largely unknown effects of many drugs on erythrocyte membrane characteristics. Thus, this matter may be even more complex because acanthocytes may not be the only erythrocytes with an aberrant shape in patients with NA or their relatives. Thus, a meaningful interpretation of acanthocytosis data is hampered by the lack of a systematic inventory of the numbers of acanthocytes and other misshapen erythrocytes in patients and nonaffected family members, as well as changes in these numbers over time.

The possible role of membrane-cytoskeleton interactions

It is not clear why erythrocytes and basal ganglia neurons are specifically affected in NA. Erythrocyte morphology depends largely on the ankyrin and junctional complexes that link the plasma membrane to the spectrin-actin cytoskeleton. Phosphorylation regulates the composition of these complexes and thereby influences the strength and type of cytoskeleton linkages. The proteins involved in erythrocyte membrane-cytoskeleton interactions are expressed in neurons. Interestingly, specific ankyrin-R splice variants and β-adducin are only expressed in brain tissue and erythrocytes. Disturbances in connectivity between the cytoskeleton and plasma membrane often have pathologic consequences for erythrocytes and may lead to neuronal death. In addition, membrane-cytoskeleton interactions and activities are regulated by lipids in both cell types. For example, the cytoskeleton proteins β-spectrin and protein 4.1 bind to both ankyrin and the phosphoinositide PtdIns(4,5)P₂ through a pleckstrin homology (PH) domain or FERM domain, respectively, and this may affect erythrocyte morphology and neuronal glutamate transporter activity.

Membrane lipid involvement

Numerous studies have focused on defining the composition and/or organization of the acanthocyte membrane. Because the main known cause of acanthocytosis is the effect of betalipoproteinemia-associated lipid metabolism disturbance, research into lipid abnormalities is an obvious focus. In general, this approach has not generated any data that clearly indicate altered lipid composition in the erythrocyte membrane as a pivotal factor in NA. Phospholipid analysis has not revealed any consistent differences in the relative amounts of the main phospholipid classes or membrane cholesterol in erythrocytes from NA patients compared with those of control donors. This statement was corroborated by a detailed semi-quantitative analysis of the erythrocyte membrane fatty acid composition. Currently available sensitive and specific mass spectrometric analysis methods to generate lipidomic data have not yet been applied to this field. However, quantitative analyses may not reveal local alterations in membrane composition (e.g., microdomain distribution and composition). In view of the known role of lipid organization in membrane behavior (see above) and the likely involvement of NBIA gene products in lipid metabolism, minor changes in lipid composition may turn out to be instrumental for the acanthocytic shape. This supposition is supported by recent findings in both yeast and human cells, showing that knockout of VPS13A (the gene that encodes chorein, the protein affected in ChAc patients) leads to a decrease in the phosphoinositide PtdIns4P. In addition, heterogeneity in the erythrocyte population, in particular the percentage of clearly identifiable acanthocytes, may have obscured the presence of cell morphology-specific alterations in lipid organization. This suggests that it may be worthwhile to reinvestigate this issue using presently available cell separation methods and lipidomic analysis technologies. Together with the known possibility of influencing membrane lipid composition—and possibly neurodegeneration—by diet interventions, molecular identification of a lipid metabolism flaw in erythrocytes would constitute an interesting starting point for the development of novel treatments.

Proteins involved in acanthocyte formation

Protein staining of the membrane fractions of erythrocytes from patients with NA has failed to reveal any conspicuous aberrations. However, immunohistochemical analyses showed consistently abnormal patterns using antibodies against band 3. Subsequent data suggested that these patterns arise from acanthocytosis-associated degradation that especially affect the N-terminal, cytoplasmic domain of band 3. It has to be noted that this approach (i.e., an investigation of acanthocytosis-associated alterations using specific antibodies) was mainly triggered by the description of altered band 3 structure and function in acanthocytosis, and this has not been systematically assessed for other erythrocyte membrane proteins. Recent data from proteomic inventories have triggered other approaches. These inventories of erythrocyte membrane fractions from patients with ChAc, MLS, and HDL-2 have revealed both acanthocytosis-associated quantitative changes in membrane protein composition revolving around band 3 and data suggesting that these changes are caused by alterations in phosphorylation-mediated protein-protein interactions. These observations led to findings suggesting that alterations in signaling pathways associated with altered membrane recruitment and/or abnormal activity of the Src-family kinase (SFK) Lyn are primarily responsible for decreased band 3-mediated binding of the cytoskeleton to the lipid bilayer in ChAc patients. A relationship between the absence of chorein, altered cytoskeleton organization, and protein phosphorylation was confirmed in a report that phosphorylation of the PI3K subunit p85 was decreased in erythrocytes from ChAc patients.
patients. This was associated with decreased phosphorylation and activation of its substrates PAK1 and Rac1 and an apparent decrease in actin polymerization.20,29

**NA pathways**

Recent years have witnessed a transition in research into NA erythrocytes from a hypothesis-driven to a phenomenological approach. The latter was almost immediately followed by investigation into the signaling pathways regulating (abnormal) protein–protein interactions in acanthocytes. This suggests that the field is influenced by the growing awareness that regulation of erythrocyte structure and function is intimately interwoven with organismal homeostasis. The emerging question is: how can the current knowledge regarding regulation of erythrocyte shape contribute to insight into the mechanisms leading to the acanthocyte shape and possibly to altered erythrocyte function? An overview of the current knowledge regarding the causes of aberrant erythrocyte morphology in genetic membraneopathies reveals many molecular and structural details regarding the interaction between integral and cytoskeletal proteins. Unfortunately, little is known about the underlying signaling pathways.6,7 Upon comparing the current knowledge on acanthocytosis with that of specific erythrocyte membraneopathies, we have to conclude that the theory that disturbance of band 3–cytoskeleton interactions induces acanthocytosis lacks sufficient heuristic value. Indeed, there is one band 3 mutation that is associated with acanthocytosis,26 but numerous others lack acanthocytes as a prominent feature. Moreover, the blood of individuals with mutations in other proteins of membrane-cytoskeleton complexes contains many more spherocytes or elliptocytes than acanthocytes.6,7 In addition, altered phosphorylation of band 3 involving Lyn and related protein kinases induces changes in band 3 organization that have not been described in acanthocytes.8,30 Finally, attempts to generate acanthocytes in vitro by disturbance of vertical and/or horizontal protein–protein interactions have not been successful. For example, disturbance of the phosphorylation status confirmed previous data that the transition from a discocyte to an echinocytic shape can be induced by increased band 3 phosphorylation,8,30 but the often postulated transition from an echinocytic to a clearly identifiable acanthocytic shape has not been published. This implies that the presence of acanthocytes is a highly specific phenomenon in patients with NA. This is the more surprising given that the known genetic causes of NA involve proteins with very diverse functions, none of which are presently known to be specific or critically important for mature erythrocytes.

**Autophagy**

An elegant model combines the various molecular details of NA into a hypothesis that centers on autophagy dysfunction.31 Indeed, flaws in autophagy have been reported in several neurodegenerative diseases11,12 and may influence erythrocyte differentiation during erythropoiesis.33 Active class I PI3K is known to inhibit autophagy,34,35 so a decrease in its activity as described in chorein-deficient cells would be expected to increase autophagy. However, such decreased activity may also constitute a compensatory mechanism, as has been postulated to explain the late onset of Huntington’s disease.36,37 Abnormal Lyn activity in ChAc erythrocytes may constitute another counteracting mechanism as Lyn activity may promote autophagy.30 The phosphoinositides PtdIns4P and PtdIns(4,5)P2 regulate membrane-cytoskeleton interactions (see above) and are emerging as important players in the autophagy process.39 The development of tools that allow on-demand lipid and kinase manipulation is needed to investigate their influence on erythrocyte shape.

**Defective erythrocyte function and brain hypoperfusion**

Most erythrocyte malformations have clinical consequences through decreased cell survival and secondary pathology,6,7 but this is much less conspicuous in patients with NA. Clinical descriptions of patients with NA concentrate on neurological and neuromuscular symptoms and are sparse in indications of hemolysis or anemia. However, decreased erythrocyte deformability and increased erythrocyte loss, as implied by splenomegaly, may be more common than suggested by the few descriptions in patients with McLeod disease.1,40 Recent in vitro findings showing decreased passage of acanthocytes and other erythrocytes from PKAN patients through a spleen-mimicking device point toward a general phenomenon.5 A reduction in haptoglobin, a marker for hemolysis, has been reported in several patients.1,40 This suggests that acanthocytes have a decreased capacity for extensive deformability.

Decreased deformability is associated with anemia, and even subclinical deformability can hamper oxygen delivery. The striatum, which is the part of the basal ganglia most severely afflicted in patients with NA, is also highly sensitive to hypoperfusion.31 Oxygen deprivation leads to excessive glutamate release in the brain and subsequent overactivation of N-methyl-D-aspartate (NMDA)-receptors and cell death. Various reports have shown that NMDA-receptor activity is increased by Src family kinases.42 Moreover, the activity of these kinases is increased under hypoxic circumstances, providing a possible explanation for abnormal Lyn activation in ChAc patients. Medium spiny neurons, the most afflicted cells in NA, are more susceptible than striatal interneurons to excitotoxic damage,43 and the selective loss of specific striatal neuronal subpopulations in a mouse model of Huntington’s disease correlates with motor symptoms similar to those observed in NA patients.14

Insufficient erythrocyte deformability, aggravated by hypoxic circumstances, may exacerbate hypoperfusion. Recent perfusion and metabolic imaging studies have shown impairment of brain perfusion in patients with sickle cell anemia,45 which may contribute to the recently observed deficiencies in cognitive functioning in sickle cell patients.46 Hypoperfusion has also been described in a NA patient using various imaging methods,47 underscoring the validity of investigating microvascular blood flow in the brain of patients with NA. Thus, hypoperfusion caused by erythrocyte dysfunction may provide a partial explanation for neuropathologic changes in patients with NA.
The where and when of acanthocyte generation have been largely neglected. Do acanthocytes evolve from normal, susceptible discocytes in circulation, or are they derived from bone marrow? Also, could NA-associated disturbance of neuronal homeostasis in the central nervous system affect erythropoiesis as suggested by reports on the involvement of nerve cells in the regulation of hematopoietic stem cell kinetics? The answers to these questions have implications for future research strategies: if acanthocytes are already formed in the bone marrow, investigation of the underlying mechanisms is likely to yield more insight, especially if we focus on genes currently known to be mutated in NA. If acanthocytes are formed in circulation, identifying the factors that induce this transition and its molecular and/or functional consequences may be more effective. From this perspective, an overview of the currently available—albeit circumstantial—evidence indicates that the acanthocytic shape may already be present upon appearance in the circulation. 1) There are no data suggesting that the acanthocytic shape increases with erythrocyte age in patients with NA. On the contrary: the percentage of acanthocytes in control donors is highest in cell fractions that contain the youngest erythrocytes. 2) There is no known association between the extent of acanthocytosis and the severity or nature of neuromuscular symptoms. 3) It has not been possible to induce acanthocytosis in vitro or to generate discocytes from patient-derived acanthocytes. 4) An increased amount of fetal hemoglobin in acanthocyte-enriched cell fractions indicates disturbed erythropoiesis in patients with NA.

Conclusion

The present overview of the available data supports the conclusion that erythrocyte-centered and acanthocyte-inspired research approaches remain instrumental to developing a better understanding of NA pathophysiology. Important goals include: 1) the effect of NA-associated mechanisms on erythrocyte structure and function, 2) a detailed comparative study of the characteristics of relevant signaling pathways in erythrocytes from patients with various forms of acanthocytosis other than ChAc, and 3) the effect of acanthocytosis on oxygen delivery.

References

1. Hermann A, Walker RJ. Diagnosis and treatment of chorea. *Curr Neurol Neurosci Rep* 2015;15:514, doi: [http://dx.doi.org/10.1007/s11910-014-0514-0](http://dx.doi.org/10.1007/s11910-014-0514-0).
2. Hayflick SJ, Westaway SK, Levinson B, et al. Genetic, clinical, and radiographic delineation of Hallervorden-Spatz syndrome. *Neu Engl J Med* 2003;348:35–40.
3. Cluitmans JCA, Tomelleri C, Yapici Z, et al. Abnormal red cell structure and function in neuroacanthocytosis. *PLoS One* 2015;10:e0125580, doi: [http://dx.doi.org/10.1371/journal.pone.0125580](http://dx.doi.org/10.1371/journal.pone.0125580).
4. Storch A, Kornhass M, Schwarz J. Testing for acanthocytosis. A prospective reader-blinded study in movement disorder patients. *J Neurol* 2005;252:84–90, doi: [http://dx.doi.org/10.1007/s00415-005-0616-3](http://dx.doi.org/10.1007/s00415-005-0616-3).
5. Reinhardt WH, Lubiszky S, Thomy S, Schulzki T. Interaction of injectable neurotropic drugs with the red cell membrane. *Toxicol In Vitro* 2014;28:1274–1279, doi: [http://dx.doi.org/10.1016/j.tiv.2014.06.008](http://dx.doi.org/10.1016/j.tiv.2014.06.008).
6. An X, Mohandas N. Disorders of red cell membrane. *Br J Haematol* 2008;141:367–375, doi: [http://dx.doi.org/10.1111/j.1365-2448.2008.07091.x](http://dx.doi.org/10.1111/j.1365-2448.2008.07091.x).
7. Costa L, Galimand J, Feneitou O, Mohandas N. Hereditary spherocytosis, elliptocytosis, and other red cell membrane disorders. *Blood Rev* 2015;27:167–178, doi: [http://dx.doi.org/10.1016/j.bler.2013.04.003](http://dx.doi.org/10.1016/j.bler.2013.04.003).
8. Ferru E, Giger K, Pantaleo A, et al. Regulation of membrane-cytoskeletal interactions by tyrosine phosphorylation of erythrocyte band 3. *Blood* 2011;117:5996–6006, doi: [http://dx.doi.org/10.1182/blood-2010-11-317024](http://dx.doi.org/10.1182/blood-2010-11-317024).
9. Cunha SR, Mohler PJ. Ankyrin protein networks in membrane formation and stabilization. *J Cell Mol Med* 2009;13:4364–4376, doi: [http://dx.doi.org/10.1016/j.jcm.2009.09.014](http://dx.doi.org/10.1016/j.jcm.2009.09.014).
10. Gilligan DM, Zozovatsky I, Gwinn B, Brugnara C, Mohandas N, Peters LL. Targeted disruption of the beta aushedin gene (Add2) causes red blood cell spherocytosis in mice. *Proc Natl Acad Sci U S A* 1999;96:10717–10722.
11. Ghavami S, Shojiari S, Yeganeh B, et al. Autophagy and apoptosis dysfunction in neurodegenerative disorders. *Prog Neurobiol* 2014;112:24–49, doi: [http://dx.doi.org/10.1016/j.pneurobio.2013.10.004](http://dx.doi.org/10.1016/j.pneurobio.2013.10.004).
12. Halstead JR, Jalink K, Dicecha N. An emerging role for Puhlns(4,5)P2-mediated signalling in human disease. *Trends Pharmacol Sci* 2005;26:654–660, doi: [http://dx.doi.org/10.1016/j.tips.2005.10.004](http://dx.doi.org/10.1016/j.tips.2005.10.004).
13. Hoover KB, Bryant PJ. The genetics of the protein 4.1 family: organizers of the membrane and cytoskeleton. *Curr Opin Cell Biol* 2000;12:229–234, doi: [http://dx.doi.org/10.1016/S0955-0674(99)00080-0](http://dx.doi.org/10.1016/S0955-0674(99)00080-0).
14. Jackson M, Song W, Liu J, et al. Modulation of the neuronal glutamate transporter EAAT4 by two interacting proteins. *Nature* 2001;410:89–93, doi: [http://dx.doi.org/10.1038/35065091](http://dx.doi.org/10.1038/35065091).
15. Machnicka B, Czogalla A, Hrynewicz-Jankowska A, et al. Spectrins: a structural platform for stabilization and activation of membrane channels, receptors and transporters. *Biochim Biophys Acta* 2014;1838:620–634, doi: [http://dx.doi.org/10.1016/j.bbamem.2013.05.002](http://dx.doi.org/10.1016/j.bbamem.2013.05.002).
16. Levy E. Insights from human congenital disorders of intestinal lipid metabolism. *J Lipid Res* 2015;56:945–962, doi: [http://dx.doi.org/10.1194/jlr.R052415](http://dx.doi.org/10.1194/jlr.R052415).
17. Clark MR, Aminoff MJ, Chiu DT, Knypers FA, Friend DS. Red cell deformability and lipid composition in two forms of acanthocytosis: enrichment of acanthocytic populations by density gradient centrifugation. *J Lab Clin Med* 1989;113:469–481.
18. Sakai T, Antoku Y, Iwashita H, Goto I, Nagamatsu K, Shi H. Chorea-acanthocytosis: abnormal composition of covalently bound fatty acids of erythrocyte membrane proteins. *Ann Neurol* 1991;29:664–669, doi: [http://dx.doi.org/10.1002/ana.409290615](http://dx.doi.org/10.1002/ana.409290615).
19. Bosman GJCGM, Bartholomeus IGP, De Grip WJ, Horstink MWIM. Erythrocyte anion transporter and antibrain immunoreactivity in chorea-acanthocytosis: a contribution to etiology, genetics, and diagnosis. *Brain Res Bull* 1994;33:523–528, doi: [http://dx.doi.org/10.1016/0361-9230(94)00078-7](http://dx.doi.org/10.1016/0361-9230(94)00078-7).
20. Park JS, Neiman AM. VPS13 regulates membrane morphogenesis during sporulation in Saccharomyces cerevisiae. *J Cell Sci* 2012;125:3004–3011, doi: [http://dx.doi.org/10.1242/jcs.105114](http://dx.doi.org/10.1242/jcs.105114).
21. Park JS, Hagegoua S, Kishida S, Neiman AM. A conserved function in phosphatidylinositol metabolism for mammalian vps13 family proteins. *PLoS One* 2015;10:e0124836, doi: [http://dx.doi.org/10.1371/journal.pone.0124836](http://dx.doi.org/10.1371/journal.pone.0124836).
22. Jansen CI, Kiliaan AJ. Long-chain polyunsaturated fatty acids (LCPUFA) from genesis to senescence: the influence of LCPUFA on neural development, aging, and neurodegeneration. *Prog Lipid Res* 2014;53:1–17, doi: http://dx.doi.org/10.1016/j.plipres.2013.10.002.

23. Hartmann T, van Wijk N, Wurtman RJ, et al. A nutritional approach to ameliorate altered phospholipid metabolism in Alzheimer’s disease. *J Alzheimers Dis* 2014;41:715–717, doi: http://dx.doi.org/10.3233/JAD-141137.

24. Bosman GJCGM, Horstink MWIM, De Grijp WJ. Erythrocyte membrane abnormalities in neuroacanthocytosis: evidence for a neuron-erythrocyte axis? In: Danek A, ed. Neuroacanthocytosis Syndromes. Springer; 2004. p. 153–159.

25. Bosman GJCGM, de Franceschi L. Neuroacanthocytosis-related changes in erythrocyte membrane organization and function. In: Walker RH, Saiki S, Danek A, eds. Neuroacanthocytosis Syndromes II; Springer; 2008. p. 133–142.

26. Kay MM, Bosman GJ, Lawrence C. Functional topography of band 3: specific structural alteration linked to functional aberrations in human erythrocytes. *Proc Natl Acad Sci U S A* 1988;85:492–496.

27. de Franceschi L, Tomelleri C, Matte A, et al. Erythrocyte membrane changes of chorea-acanthocytosis are the result of altered Lyn kinase activity. *Blood* 2011;118:5652–5663, doi: http://dx.doi.org/10.1182/blood-2011-05-353339.

28. Foller M, Hermann A, Gu S, et al. Chorein-sensitive polymerization of cortical actin and suicidal cell death in chorea-acanthocytosis. *FASEB J* 2012;26:1526–1534, doi: http://dx.doi.org/10.1096/fj.11-198317.

29. Shikawa N, Nakamura M, Sameshima M, et al. Chorein, the protein responsible for chorea-acanthocytosis, interacts with β-adducin and β-actin. *Biochem Biophys Res Commun* 2013;441:96–101, doi: http://dx.doi.org/10.1016/j.bbrc.2013.10.011.

30. Ferru E, Pantaleo A, Carta F, et al. Thalassemic erythrocytes release microparticles loaded with hemichromes by redox activation of p72Syk kinase. *Haematologica* 2014;99:570–578, doi: http://dx.doi.org/10.3324/haematol.2013.084533.

31. Prohaska R, Sibon OCM, Rudnicki DD, et al. Brain, blood and iron: perspectives on the roles of erythrocytes and iron in neurodegeneration. *Neurobiol Dis* 2012;46:607–624, doi: http://dx.doi.org/10.1016/j.nbd.2012.03.006.

32. Chu CT, Plowey ED, Dagda RK, Hickey RW, Cherra SJ 3rd, Clark RS. Autophagy in neurite injury and neurodegeneration: in vitro and in vivo models. *Methods Enzymol* 2009;453:217–249, doi: http://dx.doi.org/10.1016/S0076-6879(08)04011-1.

33. Mortensen M, Ferguson DJ, Edelmann M, et al. Loss of autophagy in erythroid cells leads to defective removal of mitochondria and severe anemia in vivo. *Proc Natl Acad Sci U S A* 2010;107:832–827, doi: http://dx.doi.org/10.1073/pnas.0913170107.

34. Petiot O, Ogier-Denis E, Blommaart EF, Meijer AJ, Codogno P. Distinct classes of phosphatidylinositol 3′-kinases are involved in signaling pathways that control macroautophagy in HT-29 cells. *J Biol Chem* 2000;275:992–998.

35. Klionsky DJ. Autophagy: from phenomenology to molecular understanding in less than a decade. *Nat Rev Mol Cell Biol* 2007;8:931–937, doi: http://dx.doi.org/10.1038/nrm2245.

36. Francelle I, Galvan L, Brouillet E. Possible involvement of self-defense mechanisms in the preferential vulnerability of the striatum in Huntington’s disease. *Front Cell Neurosci* 2014;8:295, doi: http://dx.doi.org/10.3389/fncel.2014.00295.

37. Kreiner G. Compensatory mechanisms in genetic models of neurodegeneration: are the mice better than humans? *Front Cell Neurosci* 2015;9:56, doi: http://dx.doi.org/10.3389/fncel.2015.00056.

38. Liu WM, Huang P, Kar N, et al. Lyn facilitates glioblastoma cell survival under conditions of nutrient deprivation by promoting autophagy. *PLoS One* 2013;8:e70804, doi: http://10.1371/journal.pone.0070804.

39. Hammond GR, Fischer MJ, Anderson KE, et al. PHF and PHF2 are essential but independent lipid determinants of membrane identity. *Science* 2012;337:727–730, doi: http://10.1126/science.1222483.

40. Rampoldi L, Danek A, Monaco AP. Clinical features and molecular bases of neuroacanthocytosis. *J Mol Med (Berl)* 2002;80:475–491, doi: http://dx.doi.org/10.1007/s00109-002-0349-z.

41. Payalbavash S, Souza LC, Wang Y, et al. Regional ischemic vulnerability of the brain to hypoperfusion: the need for location specific computed tomography perfusion thresholds in acute stroke patients. *Stroke* 2011;42:1255–1260, doi: http://dx.doi.org/10.1161/STROKEAHA.110.600940.

42. Salter MW, Pitcher GM. Dysregulated Src upregulation of NMDA receptor activity: a common link in chronic pain and schizophrenia. *FEBS J* 2012;279:2–11, doi: http://dx.doi.org/10.1111/j.1742-4658.2011.08390.x.

43. Mitchell IJ, Griffiths MR. The differential susceptibility of specific neuronal populations: insights from Huntington’s disease. *IUBMB Life* 2003;55:293–298, doi: http://dx.doi.org/10.1080/1521654031000153012.

44. Canals JM, Pineda JR, Torres-Peraza JF, et al. Brain-derived neurotrophic factor regulates the onset and severity of motor dysfunction associated with enkephalinergic neuronal degeneration in Huntington’s disease. *J Neurosci* 2004;24:7727–7739, doi: http://dx.doi.org/10.1523/JNEUROSCI.1197-04.2004.

45. Deus-Silva L, Bonilha L, Damasceno BP, et al. Brain perfusion impairment in neurologically asymptomatic adult patients with sickle-cell disease shown by voxel-based analysis of SPECT images. *Front Neurol* 2013;4:207, doi: http://dx.doi.org/10.3389/fneur.2013.00207.

46. Mackin RS, Insel P, Truran D, et al. Neuroimaging abnormalities in adults with sickle cell anemia: associations with cognition. *Neuro* 2014;82:835–841, doi: http://dx.doi.org/10.1212/WNL.0000000000000188.

47. Long X, Xiong N, Zhu Q, et al. Functional neuroimaging might enable the early diagnosis of neuroacanthocytosis. *Can J Neurol Sci* 2014;41:402–404.

48. Bruckner K. Blood cells need glia, too: a new role for the nervous system in the bone marrow niche. *Cell Stem Cell* 2011;9:493–495, doi: http://dx.doi.org/10.1016/j.stem.2011.11.016.

49. Morrison SJ, Scadden DT. The bone marrow niche for haematopoietic stem cells. *Nature* 2014;505:327–334, doi: http://dx.doi.org/10.1038/nature12984.