Neurobiology of Aging 66 (2018) 158–164

Contents lists available at ScienceDirect

Neurobiology of Aging

journal homepage: www.elsevier.com/locate/neuaging

Review

Cerebral microhemorrhages due to traumatic brain injury and their effects on the aging human brain

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ARTICLE INFO

Article history:
Received 12 November 2017
Received in revised form 24 February 2018
Accepted 27 February 2018
Available online 6 March 2018

Keywords:
Traumatic brain injury
Aging
Hemorrhage
Microbleed
Susceptibility-weighted imaging
Magnetic resonance imaging

ABSTRACT

Although cerebral microbleeds (CMBs) are frequently associated with traumatic brain injury (TBI), their effects on clinical outcome after TBI remain controversial and poorly understood, particularly in older adults. Here we (1) highlight major challenges and opportunities associated with studying the effects of TBI-mediated CMBs; (2) review the evidence on their potential effects on cognitive and neural outcome as a function of age at injury; and (3) suggest priorities for future research on understanding the clinical implications of CMBs. Although TBI-mediated CMBs are likely distinct from those due to cerebral amyloid angiopathy or other neurodegenerative diseases, the effects of these 2 CMB types on brain function may share common features. Furthermore, in older TBI victims, the incidence of TBI-mediated CMBs may approximate that of cerebral amyloid angiopathy-related CMBs, and thus warrants detailed study. Because the alterations effected by CMBs on brain structure and function are both unique and age-dependent, it seems likely that novel, age-tailored therapeutic approaches are necessary for the adequate clinical interpretation and treatment of these ubiquitous and underappreciated TBI sequelae.

1. Introduction

Traumatic brain injury (TBI) is a potentially serious condition of substantial epidemiological and clinical significance. The neural and cognitive consequences of TBI can be serious regardless of the victim's age at injury, although sequelae are particularly debilitating in older adults (Harvey and Close, 2012). For illustration, TBIs occur in over 5% of individuals over the age of 60 years and carry far greater morbidity and mortality in this age group than in younger cohorts (Ghorbani et al., 2014). Even after adjusting for injury type and severity, every decade of life increases the likelihood of poor clinical outcome after TBI by as much as ~50% (Hukkelhoven et al., 2003), and older patients are significantly more likely to die from TBI than younger victims (Cheng et al., 2014; Gerber et al., 2009). TBI also accelerates brain aging and the degradation of neural function (Irimia and Van Horn, 2015; Irimia et al., 2013a,b), with an average difference between survivors' chronological age and their biological brain age of ~5 years (Cole et al., 2015). Furthermore, a recent large-scale study of nearly 13,000 patients suggests that TBI increases the pathogenic hazard ratio for neurodegenerative diseases by a factor greater than 3 (Chu et al., 2016).

Cerebral microhemorrhages (or microbleeds, CMBs) constitute a ubiquitous manifestation of TBIs of all severities and their presence is strongly associated with that of traumatic axonal injury (TAI) (Glushakova et al., 2014; Liu et al., 2014). Hay et al. (2015) indicate that 40% of patients dying in the acute phase of TBI and 47% of those who survive TBIs to live for 1 year or more show multifocal, perivascular, and parenchymal CMBs in the gray matter (GM), where (1) long-range axonal connections terminate and (2) brain tissue is subjected to a substantial gradient of physical momentum during traumatic events. Mounting evidence suggests that CMBs are implicated in the pathogenesis of cerebral amyloid angiopathy (CAA) (Fu et al., 2013), an increasingly supported hypothesis whose potential implications are mirrored by epidemiological findings to the effect that CMB occurrence may increase dementia risk by a factor of at least ~1.7 (Lee et al., 2013). Simultaneously, mild TBI (mTBI) survivors who exhibit CMBs during the acute stage of injury are ~1.5 times more likely to suffer from Parkinson's disease (Gardner et al., 2014, 2015), and their mortality rate is much higher than that of the general population, with an associated hazard ratio of ~1.5 (Fuller et al., 2016).

This review describes the cellular mechanisms and potential consequences of CMBs during senescence and suggests avenues for future inquiry within this significant yet underprioritized field of

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https://doi.org/10.1016/j.neurobiolaging.2018.02.026

research. The challenges of ascertaining the extent to which the CMBs of older TBI victims are associated with either TAI or CAA are highlighted, and potential strategies for answering this important question are proposed. Based on existing evidence, we argue that, in older adults, the incidence of TAI-mediated CMBs can be similar to that of CAA-related CMBs, and may therefore be important for detailed future study. Here and throughout, TBI-mediated CMBs refer to white matter (WM) injuries or, more precisely, to susceptibility-weighted imaging (SWI)–detectable WM hypointensities associated with CMBs after TBI.

1.1. Mechanisms of CMB occurrence

Intracerebral hemorrhages were known to science as early as the 17th century, when Johann Jacob Wepfer (1620–1695) found fragile vessels in relation to a large cerebral hemorrhage, but was unable to identify a point of rupture (Alg and Werring, 2011). By 1868, Charcot and Bouchard had analyzed the content of microaneurysms, and the impact of CMBs became even more widely acknowledged once Ramon y Cajal (1928) had described the neurotoxic effects of blood extravasation. Among these effects is the phenomenon of neural tissue necrosis, which involves the death of neural cells, whose severity increases substantially as the brain ages and whose sequelae last longer as the effectiveness of neural repair mechanism declines (Morrison and Hof, 1997). The formation of CMBs is thought to involve diapedesis, whereby erythrocytes transiently cross the endothelium of the blood-brain barrier (BBB) to form hemosiderin and/or ferritin deposits within petechiae of the cerebral parenchyma (Zhang et al., 2014). The time rate of diapedesis is strongly dependent on BBB permeability, which is typically greater in males (Pakulski et al., 2000), begins to increase significantly after the age of 45 years (Blennow et al., 1993), and may be 2 to 3 times higher after the age of 60 years compared with the age of 30 years (Rosenberg, 2014). Thus, the higher permeability of the BBB in older TBI patients has long been acknowledged as an important factor contributing to the severity of postinjury brain tissue damage (Farrall and Wardlaw, 2009).

Although CMBs themselves are focal, research indicates that diapedesis effects can extend far outside the penumbra of the microhemorrhage itself, that is, outside the immediate CMB neighborhood (Patel et al., 2010; Simard et al., 2009). Recent studies additionally suggest that penumbral radii are more extensive in older adults, which may reflect the higher probability that BBB breakage increases the severity of TBI sequelae in this patient group (Hawkins and Davis, 2005). Although penumbral microvasculature may receive damage during impact, which is insufficient to rupture the BBB, subsequent molecular response mechanisms can maladaptively cause the subsequent structural failure of these particularly vulnerable capillaries. Such a phenomenon may lead to the delayed formation of petechial hemorrhages, which can coalesce to form iron deposits and then lead to serious complications, including hemorrhagic progression (Kurland et al., 2012). The iron deposits formed after BBB breakage typically result from the phagocytosis of erythrocytes, whereby heme iron in ferritin (i.e., iron bound to heme cofactors within certain proteins, including hemoglobin) is degraded and deposited in the form of hemosiderin. As part of the exogenous inflammatory response to injury, neutrophils may phagocytize and thereby clear cellular debris but may also release free radicals which harm other parenchymal cells and thereby propagate tissue injury (Whitney et al., 2009).

1.2. Structural sequelae and mechanisms of deterioration

Current research indicates that, during senescence, microhemorrhages localized to the cerebral parenchyma are associated with focal permeability of the BBB and with potentially dramatic reorganization of neuronal connectivity, even decades after injury (Glushakova et al., 2014). Because blood vessels are typically more elastic than axons (Spedden et al., 2012; VanBavel et al., 2003), CMB presence has been proposed to be associated with TAI, although the former has not been established unambiguously as primary evidence of the latter. First, higher axonal elasticities do not translate into lower thresholds for their shearing and tearing as a result of acceleration and deceleration forces to which the brain is subjected during physical impact (Arfanakis et al., 2002). Second, it is possible that CMB-associated WM damage and/or necrosis may be the result of secondary ischemia rather than the consequence of primary axonal injury (Raghupathi, 2004). Nevertheless, because both the mechanical stiffness and the threshold for capillary rupture increases with age (Sawabe, 2010), the frequency of CMB occurrence after TBI is likely to increase throughout senescence and may additionally be associated with TAI far more often than in youth. Ultimately, histological examination remains the method of choice for ascertaining the biology of WM responses associated with CMBs. Preliminary results from the laboratory of one of the authors (AI) suggest that, even in mTBI, CMBs can be associated with substantial macroscale WM alterations in older adults, which may not resolve with time (Fig. 1).

An important characteristic of TBI-mediated CMBs is that they frequently occur at the boundary between cortical GM and WM. This is partly due to the distinct mechanical responses of these 2 tissue types as they are subjected to large physical forces and partly to differences in venous drainage at the GM-WM boundary (Liu et al., 2014). Because the GM-WM interface is sometimes superficial (superior frontal gyri, middle temporal gyri, etc.) or, other times, deep (insulae, cingulate gyri, etc.) relative to the scalp, one implication of both TBI biomechanics and human neuroanatomy is that the spatial distribution of CMBs throughout the cerebrum can be widespread and/or difficult to anticipate across patients, as confirmed by Hay et al. (2015). Owing to the large number of long-range, intrahemispheric WM connections (e.g., corticospinal tract, arcuate fasciculus, corona radiata), CMBs can be associated with highly-widespread TAI even in mTBI patients (Liu et al., 2014), and their number and size can be greater in older patients compared with younger adults for reasons previously discussed.

Although it has been consistently acknowledged that older age at the time of TBI is usually associated with decreased ability for recovery from CMBs (Miller et al., 2017; Stocchetti et al., 2012), the biological mechanisms involved in this phenomenon remain insufficiently understood. It appears that older individuals' relatively poor ability to recover from insults to the microvasculature is strongly modulated by their frequently-deficient endocrine reactions and by their broader neuroinflammatory responses compared with younger victims. For example, proinflammatory cytokines downregulate physiological responses to a variety of hormones, including insulin, somatotropin, insulin-like growth factor, thyroid hormone, and estrogens (Ferrucci et al., 2004). On the one hand, the attenuation of these and other neuroendocrine processes, which occurs with aging, has an appreciable effect on the reduced ability of the brain to recover from TBI (Cekic and Stein, 2010). On the other hand, whereas microglia play a prominent role in neuroinflammation, their mechanisms of action are greatly affected by aging in numerous ways, which include the alteration of both microglial morphology and of phagocytic activity (Linehan and Fitzgerald, 2015). Together, these phenomena lead to greater oxidative stress and increased cytokine production (Mosher and Wyss-Coray, 2014). Partly for such reasons, older adults with acute TBI have higher cytokine levels and more phagocytosis-deficient microglia than younger adults (Ritzel et al., 2015).

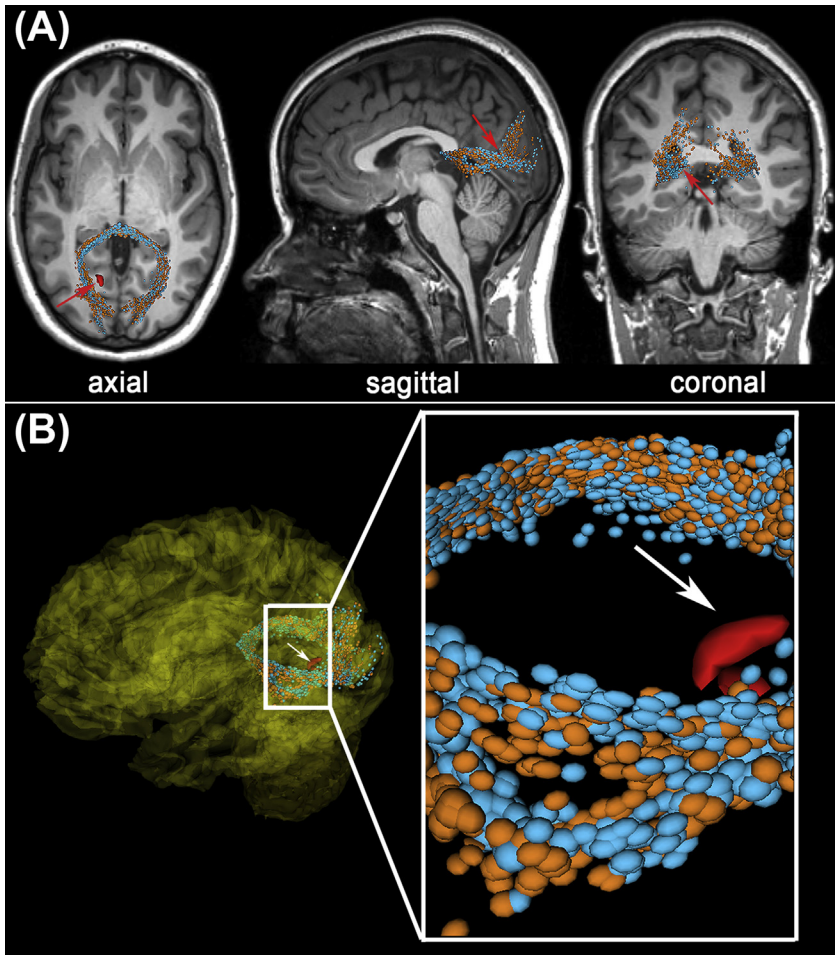

Fig. 1. Representative example of DTI streamlines passing through the vicinity of a ~4 mm^3 CMB (red) in an old adult victim of mTBI. Arrows indicate a CMB in the left hemisphere, close to a streamline bundle belonging to the splenium of the corpus callosum. (A) Standard views (coronal, sagittal, and axial) of T_1-weighted MRI are shown in addition to DTI glyphs associated with perilesional WM streamline bundles imaged acutely (orange) and approximately 6 months after injury (light blue). The splenium is notably asymmetric at both time points, with the asymmetry being most pronounced close to the CMB (inset). (B) Splenial streamlines ipsilateral to the CMB diverge briefly in its vicinity, and this is not found to occur contralateral to the CMB (inset). This asymmetry is also found at the time of the chronic scan. Abbreviations: DTI, diffusion tensor imaging; CMB, cerebral microbleed; mTBI, mild traumatic brain injury; MRI, magnetic resonance imaging; WM, white matter. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Prior research in older TBI victims describes the downregulation of numerous genes involved in B-lymphocyte and $CD4^+$ T-cell activity after CMB occurrence—compared with the upregulation of such genes in younger patients—and partly explains why both B-cell and immunoglobulin counts are lower in older TBI survivors than in younger ones (Ritzel et al., 2015). In addition, during the acute stage of TBI, regulatory inflammatory genes such as leucine zipper transcription factor 2, leucine-rich repeat neuronal 3, and lymphoid enhancer-binding factor 1 are expressed at higher levels in younger TBI patients (Ritzel et al., 2015). By contrast, older TBI victims exhibit increased transcriptional activity associated with S100 family genes, including S100 calcium-binding proteins P (S100P) and A8 (S100A8). These 2 genes are expressed in activated macrophages and microglia and have been linked to poor recovery from TBI due to the increased inflammatory response modulated by these cell types (Beschorner et al., 2000). Unsurprisingly, older adults also exhibit reduced activity of members from the transforming growth factor β family, which are linked to neural recovery and regeneration. These gene expression differences between younger and older adults mirror the higher frequency of positive clinical findings on the chronic brain imaging scans of older TBI survivors (Cho et al., 2016) and suggest a direct association between immune regulation and brain recovery as a function of age at injury.

An essential and underappreciated aspect of TBI in aging adults is the fact that brain responses to it can extend over years and even decades (Van Horn et al., 2018). For example, human neuroimaging scans have confirmed that (1) TBI-activated microglia may persist in the brain for as long as 2 decades after injury (Jacobowitz et al., 2012; Ramlackhansingh et al., 2011); (2) cerebral inflammation can last for many years, with numerous deleterious effects on brain function (Johnson et al., 2013); and (3) new microvascular abnormalities can appear on common basis even long after injury (Fujita et al., 2012). Together, these phenomena appear to delineate a complex and poorly understood cascade of cellular events which contribute to delayed neural repair despite potentially deceiving appearances, which may suggest that some patients have fully recovered.

1.3. Neuroradiological identification

In clinical settings, a common approach to CMB detection involves the use of SWI, a type of magnetic resonance imaging (MRI) which is highly sensitive to iron accumulation in the body. SWI uses a fully flow-compensated, gradient-recalled echo pulse sequence which exploits magnetic susceptibility differences between tissues to produce enhanced contrast magnitude MRI images of venous

blood, hemorrhages, and iron storage complexes (Haacke et al., 2009; Mittal et al., 2009). In SWI, CMBs can be defined as ovoid, hypointense, neuroanatomic foci, which are inconsistent with osseous, vascular, or MRI-related artifacts (Liu et al., 2014). MRI techniques such as magnetic field correlation imaging, quantitative susceptibility mapping, and field-dependent relaxation rate increase imaging can additionally quantify diffuse nonheme iron deposition throughout the parenchyma in vivo and can, therefore, be used to supplement SWI-provided information on CMBs (Haacke et al., 2015; Raz et al., 2011).

In clinical settings, an increasingly prominent strategy for identifying CMB-related TAI involves diffusion MRI techniques such as diffusion weighted, diffusion tensor, and diffusion spectrum imaging (DWI, DTI and DSI, respectively). These methods can quantify the preferential direction of water diffusion throughout the brain and thereby identify the locations of physical insults to WM connections. Mapping TAI associated with CMBs can provide clinical and scientific insight above and beyond the ability of more traditional modalities to do so (Scheid et al., 2006). For example, computed tomography and conventional MRI (including T_1-, T_2-,and T_2^*-weighted MRI and even GRE or fluid-attenuated inversion recovery (FLAIR) imaging) can routinely isolate relatively large, intraparenchymal hemorrhages. These techniques, however, do not allow either short- or long-term changes in WM connectivity to be assessed with quantitative precision, whereas diffusion MRI can greatly assist this task (Irimia et al., 2011).

An important challenge related to the identification of TBI-mediated CMBs in older adults is that a substantial subset of the aging population may have CAA-related CMBs before injury. For example, CMBs are present in ~6% of randomly selected, asymptomatic individuals over the age of 60 years who do not have a history of neuropsychiatric disease (Koennecke, 2006). Although the simultaneous existence of both TBI- and CAA-related CMBs may confound research efforts aimed at quantifying injury-related CMBs, some distinctions exist between these 2 forms of pathology. For example, CAA-related CMBs occur more often in deep and infratentorial regions due to hypertensive arteriopathy (Greenberg et al., 2009), or in posterior brain regions (occipital lobe, in particular) due to vascular beta amyloid depositions (Johnson et al., 2007). In addition, areas commonly affected by CAA-related CMBs include the mid-subcortical cerebrum and the areas superior to the corpus callosum (Huang et al., 2015; Yates et al., 2014). On the other hand, TBI-mediated CMBs occur more often at the boundary between GM and WM (Liu et al., 2014), in brain regions where primary (e.g., coup and/or contrecoup) injuries are located (Huang et al., 2015), or in midline regions, particularly above the corpus callosum or in medial subcortex (Imaizumi et al., 2011).

1.4. Clinical significance

The clinical implications of CMBs in older adults are controversial. Broadly speaking, available scientific and clinical knowledge suggests that post-traumatic CMBs have substantial negative effects on the aging central nervous system and that the severity of their impact increases with patients' age at injury. Specifically, in older adults with mTBI, the higher permeability of the BBB, the attenuation of neuroendocrine processes (e.g., those responsible for releasing somatostatin and insulin-like growth factor), and the maladaptive neural repair responses of the aging brain to injury are likely to contribute substantially to this population's poorer trajectory of recovery compared with that observed in younger patients. Although neuroradiological examinations of mTBI patients identify CMBs relatively frequently even years after injury—which can facilitate the task of monitoring the temporal dynamics of these phenomena—the long-term consequences of CMBs remain rather obscure (Huang et al., 2015). The association between CMB presence and clinical outcome in mTBI patients remains particularly controversial (Charidimou et al., 2013; Scheid et al., 2006; Talavage et al., 2015), whereas the specific ways in which this type of hemorrhage differentially affects the aging brain remain inadequately explored. Some studies suggest a correlation between CMB presence and TBI-related deficits (Geurts et al., 2012; Toth et al., 2012), whereas others have been ambivalent regarding the clinical relevance of small hemorrhagic lesions (Yuh et al., 2013). Some insights into this matter may be gained from pediatric TBI studies. Specifically, CMBs which arise in typically-developing children after TBI are statistically associated with neural and cognitive deficits (Salehi et al., 2017), and this suggests that the functional effects of CMBs in older adults may be like those in children (although potentially more pronounced due to aging processes).

In the aging brain, where the cerebral microvasculature is increasingly sensitive to mechanical stress (Sawabe, 2010), CMB occurrence after TBI is allegedly more consequential than in younger cohorts (Greenberg et al., 2009). In patients with moderate-to-severe TBI, the negative effects of isolated CMBs on clinical outcome may not initially seem to be nearly as dramatic as those of far larger hemorrhagic and/or non-hemorrhagic lesions. This intuitive argument, however appealing, does not account for the complex and potentially substantial changes effected by CMB-related TAI on brain regions located far from primary injury sites. Given that such dynamic alterations can substantially affect both cognitive and neural function (Palacios et al., 2011), more research is needed to understand the relationship between the presence of CMBs in the TBI brain and long-term effects on high-order brain functions.

In older patients with mTBI, the associations between CMBs, histopathology, and clinical outcome are particularly difficult to quantify and prognosticate, especially in individuals with negative clinical findings on T_1- and/or T_2-weighted MRI. One cause of this difficulty is that postmortem neuropathologic examinations are rarely available from mTBI patients who die of other causes. In the very few such cases which have been reported, histopathological examinations have revealed the presence of hemosiderin-laden macrophages in perivascular GM and WM, suggesting that axonal shearing is the primary mechanism of mTBI-related brain damage (Bigler, 2004). In mTBI patients with CMBs, significant correlations have been identified between the number of WM fasciculi damaged by TAI and the magnitudes of delays in cognitive reaction times, which appear to increase with age (Niogi et al., 2008). It seems, thus, that further research is required to (1) assess the prognostic value of CMB quantitation relative to that of DTI-based connectivity analysis and to (2) disentangle the potential clinical utility of these 2 approaches as a function of victim age at injury.

Some argue (Yates et al., 2014) that there is no definite way to determine CMB chronicity in TBI patients. However, progress in this direction could be made by using neuroimaging to monitor populations at high risk for TBI (e.g., contact-sports athletes). First, such monitoring could afford comparison of mTBI victims' baseline scans to their postinjury MRI readings and could thereby allow researchers to distinguish recently acquired CMBs from older ones. Second, because TBI-mediated CMBs may not be readily distinguishable from microhemorrhages associated with CAA, factorial design studies (factors: CAA, TBI) may be useful for understanding the associative relationship and interaction between these 2 pathology types, as well as the putative differences in their effects on neural function. We propose that, barring severe neurovascular or neurodegenerative pathology, TBI-mediated CMBs can be equally—if not more—common in older TBI victims than those associated with CAA. Confirmation of this hypothesis would suggest that renewed efforts should be dedicated to understanding CMB effects

on the TBI-affected brain, preferably in the context of studies where TBI victims and TBI-free volunteers can be stratified based on their risk factors for CAA. This strategy could allow researchers to control for the confounding effects of such risk factors when assessing differences in CMB count, spatial distribution, and prevalence between the 2 populations. Importantly, the extent to which cognitive reserve modulates post-traumatic neurodegeneration and/or recovery—whether in the presence or absence of CAA—has not been explored sufficiently (Griesbach et al., 2018), and future research should accommodate and examine this important neuropsychological measure.

1.5. Relationship to neurodegeneration

Microvascular damage has long been associated with neurodegeneration (Cordonnier and van der Flier, 2011). For example, the brains of aging adults with a history of repeated TBIs exhibit hemosiderin deposits and accumulations of tau protein in the direct vicinity of blood capillaries (McKee et al., 2009). Such patients have been found to experience accelerated demyelination, extensive accumulation of tau-positive neurofibrillary tangles, nonheme iron deposition as well as widespread vascular damage (Nisenbaum et al., 2014). In many TBI patients, the extent and spatial pattern of these phenomena are often reminiscent of those observed in TBI-free individuals affected by cognitive impairment (Schrag et al., 2010). Amyloid deposits are also commonly found within microhemorrhagic foci in mouse models and human familial Alzheimer's disease (Cacciottolo et al., 2016; Finch and Shams, 2016).

TBI-mediated CMBs are clearly distinct from those due to CAA or other neurodegenerative diseases, only based on the criterion of their causative factors. Nevertheless, the effects of these 2 CMB types on brain function may share common features beyond those related to the mechanisms of their occurrence, and may additionally implicate their effects on brain function. In this respect, the extent to which TBI-mediated CMBs can contribute to or even aggravate CAA and neurodegeneration in general has not been quantified adequately. To this end, future studies should compare mTBI survivors to TBI-free control volunteers while stratifying all participants based on their CAA-related environmental risk factors. This approach could provide valuable insights into the differential effects of CAA-versus TBI-mediated CMBs on attention, executive control and memory, all of which are frequently impacted in both TBI- and CAA-related neurodegeneration and cognitive degradation, although potentially in distinct ways. It is reasonable to hypothesize that knowledge of cognitive reserve at the time of injury can assist in determining the probability that SWI-detectable CMBs are related to either CAA or TBI. If this is indeed the case, this important neuropsychological measure could allow researchers to examine the relationship between CAA and older adults' vulnerability to CMBs after TBI.

Apolipoprotein E polymorphisms modulate many neuroinflammatory responses and accelerate neurodegenerative pathology after TBI (Laskowitz et al., 2010). These factors may modulate CMB evolution as well; in animal models, DTI measures of WM damage have been linked to physical insults effected on axons stained with amyloid precursor protein, to loss of myelination, to increased permeability of neuronal membranes, and to other forms of pathology which are commonly observed in neurodegenerative diseases (Mac Donald et al., 2007; Povlishock and Katz, 2005). As in such conditions, the survivors of repeated TBI exhibit substantial, redox-active nonheme iron deposition in the hippocampus and within inferior temporal cortex (Bouras et al., 1997). These patients often also feature chronic upregulation of heme oxygenase 1 (HO-1), an enzyme which degrades heme-bound iron into free iron and contributes to iron overload (Wu et al., 2003). HO-1 is well documented as a macromolecule involved in the pathologies of several neurodegenerative disorders of aging, where its upregulation promotes astrocytic iron accumulation, oxidative stress, and mitochondrial iron sequestration (Schipper, 2004).

Older adults' unique structural and functional changes prompted by mTBI-mediated CMBs, however, may indicate that tailored therapeutic approaches are likely necessary for their adequate treatment. To acquire detailed understanding of how microhemorrhages can cause or aggravate secondary brain injury in older adults, future studies should investigate the mechanisms whereby HO-1 mediates such phenomena as a function of age. Furthermore, because neural responses to mTBI may persist for decades after injury and contribute to patients' susceptibility to neurodegenerative diseases such as Alzheimer's disease and Parkinson's disease, understanding why and how the brain ages faster after mTBI should be prioritized as a significant research goal.

2. Conclusions

The literature on the topic reviewed here suggests several important directions for future research. First, more basic science studies should attempt to alleviate CMB sequelae in animal models of the TBI-affected, aging brain. We identify 8 major specific aims in this respect, namely (1) promoting therapeutic revascularization; (2) reducing cytokine levels in CMB-affected regions; (3) interrupting the degradation of heme-bound iron; (4) alleviating oxidative stress at BBB breakage locations; (5) stimulating macrophages' phagocytic ability; (6) increasing immunoglobulin production; (7) decelerating neurofibrillary tangle deposition in the CMB (pen)umbra; and (8) stimulating the remyelination of TAI-affected axons in the CMB (pen)umbra.

Older adults' relatively high vulnerability to TBI-mediated CMBs indicates that next-generation therapeutic interventions should be tailored to the specific needs of this particularly vulnerable population. Such interventions should aim to reduce aging-related deficiencies in the brain's systemic response to injury and to accommodate the potentially serious implications of CMBs. Historically, no clinical trial evaluating neuroprotective compounds for the treatment of TBI has been successful (Marklund and Hillered, 2011), partly because the clinical efficacy of many such compounds hinges on their administration before—rather than after—TBI (Menon, 2009). Nevertheless, research aimed at reversing microvascular damage in the aging brain has identified compounds which can promote therapeutic revascularization even if administered after TBI. One such compound is fucoidan, a fucose-based sulfated polysaccharide which can reduce neuronal apoptosis, lipid peroxidation, reactive oxygen species generation and mitochondrial dysfunction (Wang et al., 2016). These observed benefic effects are possibly mediated by the activation of SIRT3, a deacetylase from the sirtuin class of proteins, which is localized within the mitochondrion and is well known for its involvement in aging processes (Preyat and Leo, 2013). Fucoidan-treated old rats exhibit significant reductions in lesion volumes as well as improvements in sensorimotor function, spatial learning and memory formation. Given the paucity of currently available lifestyle interventions which can specifically target hemorrhagic lesions in TBI patients, the efficacy of this and other compounds with similar benefic effects should be studied in detail.

From a neuroimaging standpoint, the ability to distinguish between CAA- and TBI-mediated CMBs using currently available MRI sequences remains a significant goal and challenge. The differences between these 2 types of hemorrhages should be investigated more actively to understand (1) the differential effects of these 2 CMB types on the aging brain; (2) the manner in which cognitive reserve modulates recovery; as well as (3) their potential interaction in modulating clinical outcome. Future MRI sequences for imaging the

TBI-affected brain in the acute stage of injury could exploit differences in structural neuropathology between "older" (CAA-mediated) and "newer" (TBI-mediated) CMBs to distinguish between the 2. Such technological capabilities could substantially enhance our ability to study how underlying CAA can modulate brain responses to TBI and may even lead to better understanding of CAA itself.

Finally, it is important to emphasize that future studies should preferentially target older TBI patients above and beyond the scope of other ongoing efforts in the field of basic, translational, and clinical brain injury research. The elderly represent a prominent and growing demographic segment of the population affected by TBI (Stocchetti et al., 2012), such that future interventions which take into account the distinct needs of older TBI survivors should be incorporated into geriatric care protocols. This could synergistically alter TBI trajectories in older victims with potentially substantial effects on patients' well being and quality of life.

Disclosure statement

The authors have no competing interests to declare.

Acknowledgements

This work was supported by the National Institutes of Health (grant numbers R01 NS 100973 to AI and R44 NS 081792 to JDVH). AI wishes to thank Prof Caleb E. Finch for his excellent and detailed suggestions, comments, and contributions, as well as for valuable discussions on the topic of this review. He also wishes to thank Kenneth A. Rostowsky and Nahian F. Chowdhury for their assistance with preparing the figure.

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