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Small Heat Shock Proteins Induce a Cerebral Inflammatory Reaction

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More than 80% of Alzheimer’s disease (AD) patients have some degree of cerebral amyloid angiopathy (CAA). In addition to arteries and veins, capillaries can also be affected. Capillary CAA (capCAA), rather than CAA in larger vessels, is associated with flame-like amyloid-beta (Aβ) deposits that may extend beyond the vessel wall and radiate into the neuropil, a phenomenon also known as “dyshoric angiopathy.” Aβ deposits in AD, parenchymal as well as (cap)CAA and dyshoric angiopathy, are associated with a local inflammatory reaction, including activation of microglial cells and astrocytes that, among others, produce cytokines and reactive oxygen species. This neuroinflammatory reaction may account for at least part of the cognitive decline. In previous studies we observed that small heat shock proteins (sHsps) are associated with Aβ deposits in AD. In this study the molecular chaperones Hsp20, HspB8 and HspB2B3 were found to colocalize with CAA and capCAA in AD brains. In addition, Hsp20, HspB8 and HspB2B3 colocalized with intercellular adhesion molecule 1 (ICAM-1) in capCAA-associated dyshoric angiopathy. Furthermore, we demonstrated that Hsp20, HspB8 and HspB2B3 induced production of interleukin 8, soluble ICAM-1 and monocyte chemoattractant protein 1 by human leptomeningeal smooth muscle cells and human brain astrocytes in vitro and that Hsp27 inhibited production of transforming growth factor beta 1 and CD40 ligand. Our results suggest a central role for sHsps in the neuroinflammatory reaction in AD and CAA and thus in contributing to cognitive decline.

Introduction

In Alzheimer’s disease (AD) amyloid-beta (Aβ) is deposited as plaques in the parenchyma, but also as cerebral amyloid angiopathy (CAA) (Selkoe, 1991). Capillary Aβ deposits (capCAA) correlates with severity of AD pathology and clinical deterioration, whereas larger vessel CAA does not (Attems and Jellinger, 2004; Eurelings et al., 2010). Furthermore, in capCAA, flame-like Aβ deposits may extend beyond the vessel wall and radiate into the neuropil, a phenomenon known as “dyshoric angiopathy” (Attems et al., 2011). Neurpathological examination of (cap)CAA reveals activated microglia and astrocytes surrounding these lesions (McGeer and McGeer, 1995; Yamada et al., 1996; Akiyama et al., 2000; Rozemuller et al., 2005; Richard et al., 2010; Attems et al., 2011) and colocalization of inflammatory factors such as intercellular adhesion molecule 1 (ICAM-1) (Verbeek et al., 1996).

In AD brains, an inflammatory reaction may occur in conjunction with Aβ deposits, characterized by the increased expression of, among others, transforming growth factor beta 1 (TGF-β1) (Wyss-Coray et al., 1997), interleukin (IL) 1β, IL-8, monocyte chemoattractant protein 1 (MCP-1), ICAM-1 and CD40 ligand (Akiyama et al., 2000; Calingasan et al., 2002; Sokolova et al., 2009; Heneka et al., 2010). This inflammatory reaction may occur in response to the presence of extracellular Aβ or phagocytosis of Aβ deposits by microglia (Malm et al., 2010). Inflammation, both directly via interaction of activated glial cells and indirectly via secreted neurotoxic mediators may compromise neuronal function. Indeed, transgenic mice with extensive CAA showed cognitive decline as a result of increased microglial activation and neuroinflammation (Xu et al., 2007). Epidemiological studies demonstrated that most patients with CAA-related inflammation show at least a partial clinical improvement to high dose corticosteroids or other immunosuppressive agents (Chung et al., 2011). Thus both human and mouse studies provide evidence for a contribution of Aβ to CAA-related neuroinflammation and subsequent cognitive decline. However, the neuroinflammatory reaction in AD patients may be more complex.

In AD, several macromolecules colocalize with plaques and CAA, including small heat shock proteins (sHsps) (Wilhelmus et al., 2011) and colocalization of inflammatory factors such as intercellular adhesion molecule 1 (ICAM-1) (Verbeek et al., 1996).
al., 2006b,c). Previous research showed that expression of αB-crystallin and Hsp27 is increased in reactive astrocytes of AD brains (Renkawek et al., 1993, 1994; Wilhums et al., 2006c). Hsp20 codeposited with αB in diffuse and classic plaques and HspB2 with classic plaques and CAA (Wilhums et al., 2006c). Moreover, HspB8 colocalized with classic plaques in AD and with CAA in hereditary cerebral hemorrhage with amyloidosis of the Dutch type (HCHWA-D) (Wilhums et al., 2006b). Furthermore, we observed that these sHsps, but not αB, induced IL-6 production in various cerebral cell cultures (Wilhums et al., 2009), suggesting that sHsps may play a pivotal role in inducing neuroinflammation. Therefore, we investigated the association of sHsps with (cap)CAA and CAA-associated inflammation in postmortem brain and investigated the effect of selected sHsps on the production of inflammatory factors by cultured human leptomeningeal smooth muscle cells and astrocytes in vitro.

Materials and Methods

Reagents. Lyophilized αB1-42 (95% pure) and αB1-40 (98% pure) were purchased from Quality Controlled Biochemicals. αB with the "Dutch" mutation (22 Glu→Gln, αB1-40: 96% pure) was purchased at 21st Century Biochemicals. αB1-40 was used as a model peptide, because it causes CAA in hereditary cerebral hemorrhage with amyloidosis of the Dutch type (HCHWA-D) (Davis and Van Nostrand, 1996; Verbeek et al., 1997; Wilhums et al., 2007). αB1-42, αB1-40, and αB1-40 were dissolved in 1,1,3,3,3-hexafluoro-2-propanol (HFIP) (Sigma-Aldrich), air-dried, and dissolved in DMSO at a concentration of 5 mM. Aliquots of the solutions were stored at −80°C.

Autopsy material. Patient selection was based on neuropathological findings at autopsy. Tissue samples were selected for the presence of capCAA (Richard et al., 2010). For immunohistochemistry, tissue samples from the occipital neocortex from 3 AD patients with capCAA (age 76 ± 12 years; postmortem delay 5:53 ± 2:09 h) were obtained after rapid autopsy and immediately frozen in liquid nitrogen. Informed consent was obtained according to European guidelines. Table 1 provides an overview of the diagnosis, Braak stage, CERAD score, CAA grade, age, postmortem interval (PMI) and gender. Neuropathological evaluation was performed on frozen tissue from occipital pole cortex. CAA score was defined as follows: severe (+ + +), moderate (+ +), mild (+) as previously described (Richard et al., 2010). Staging of AD was evaluated according to the criteria established by Braak and Braak and CERAD (Braak and Braak, 1991; Mirra et al., 1991).

Immunohistochemistry. In Table 2 the primary antibodies used in this study are listed. Unless mentioned otherwise, we used biotin-labeled horse anti-mouse antibodies (Vector Laboratories) as the detection antibody for mouse monoclonal antibodies, or biotin-labeled goat-anti-rabbit antibodies (Vector Laboratories) in the case of rabbit polyclonal antibodies.

Serum cyrossections (4 μm) were air-dried and fixed in acetone for 5 min. Endogenous peroxidase activity was blocked using acetone containing 0.15% H2O2 for 5 min. Sections were preincubated for 30 min with 20% animal serum, the type of which was determined by the specific biotin-labeled antibody used. Subsequently, sections were incubated overnight at 4°C with primary antibody (Table 2), with secondary antibodies for 60 min at room temperature, and with the avidin-biotin complex according to the manufacturer’s description. Between incubation steps, sections were extensively washed using PBS. 3-Amino-9-ethyl carbazole (AEC) was used as a chromogen. After a short rinse in tap water the preparations were incubated with hematoxylin for 1 min and thoroughly washed with tap water for 10 min. Finally, sections were mounted with Immol mount (Klinipath). All antibodies were diluted in PBS containing 1% bovine serum albumin (BSA), which also served as a negative control. At regular intervals, sections were stained with anti-αB to allow for topographical alignment of CAA with the stains for sHsps and inflammatory factors.

For double immunostaining of αB and/or astrocytes/microglia, sections were stained using the EnVision method as previously described (Richard et al., 2010). Briefly, sections were incubated overnight at 4°C with primary antibodies (Table 2), followed by incubation with EnVision HRP. EnVision 3,3-diaminobenzidine (DAB) was used as chromogen. Antibodies were diluted in PBS/1% BSA, which also served as a negative control. After each incubation, slides were extensively washed with PBS. For the detection of fibrillar αB in plaques and CAA, sections were stained with Congo Red (0.5% in Ethanol 80%, 3% NaCl) for 20 min at room temperature. Finally, sections were mounted with DePeX mounting medium Gurr.

Table 1. Overview of the origin of astrocyte and HBP cell cultures and tissue sections

<table>
<thead>
<tr>
<th>Number</th>
<th>Diagnosis</th>
<th>Age (years)</th>
<th>PMI (h)</th>
<th>Gender</th>
<th>NFT stage (Braak)</th>
<th>Plaque score (CERAD)</th>
<th>CAA grade</th>
<th>Cell type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AD</td>
<td>84</td>
<td>6:30</td>
<td>V</td>
<td>C</td>
<td>N.D.</td>
<td>Astrocyte</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>AD</td>
<td>92</td>
<td>7:00</td>
<td>F</td>
<td>V</td>
<td>O</td>
<td>N.D.</td>
<td>Astrocyte</td>
</tr>
<tr>
<td>3</td>
<td>Control</td>
<td>76</td>
<td>4:40</td>
<td>F</td>
<td>I</td>
<td>B</td>
<td>N.D.</td>
<td>Astrocyte</td>
</tr>
<tr>
<td>4</td>
<td>AD</td>
<td>77</td>
<td>3:00</td>
<td>M</td>
<td>VI</td>
<td>C</td>
<td>++</td>
<td>SMC</td>
</tr>
<tr>
<td>5</td>
<td>Parkinson</td>
<td>91</td>
<td>4:00</td>
<td>F</td>
<td>V</td>
<td>C</td>
<td>++</td>
<td>SMC</td>
</tr>
<tr>
<td>6</td>
<td>Control</td>
<td>83</td>
<td>4:00</td>
<td>F</td>
<td>III</td>
<td>B</td>
<td>-</td>
<td>SMC</td>
</tr>
</tbody>
</table>

IHC

| 7 | AD + CAA | 65 | 7:20 | M | V | C | ++ | N.A. |
| 8 | AD + CAA | 89 | 6:35 | F | V | C | ++ | N.A. |
| 9 | AD + CAA | 74 | 3:25 | M | VI | C | ++ | N.A. |
| 10 | Control | 81 | 3:45 | M | I | 0 | - | N.A. |
| 11 | Control | 71 | 6:05 | F | III | C | - | N.A. |
| 12 | Control | 92 | 6:25 | F | III | A | + | N.A. |

Overview of the cases used in this study. IHC. Tissue used for immunohistochemistry: F. Female; M, male; N.D., not determined; N.A., not applicable. Grading of AD (Braak scores) was performed as described in Materials and Methods.

Table 2. Primary antibodies used in this study

<table>
<thead>
<tr>
<th>Primary antibody</th>
<th>Antigen</th>
<th>Species raised in</th>
<th>Dilution</th>
<th>Source (reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6C6</td>
<td>αB</td>
<td>Mouse</td>
<td>1:250</td>
<td>Dr. Schenk, Elan Pharmaceuticals</td>
</tr>
<tr>
<td>GFAP</td>
<td>GFAP</td>
<td>Mouse</td>
<td>1:10</td>
<td>Monosan, Sanbio</td>
</tr>
<tr>
<td>LN3</td>
<td>HLA-DR</td>
<td>Mouse</td>
<td>1:50</td>
<td>ebioscience</td>
</tr>
<tr>
<td>MAB208</td>
<td>IL-8</td>
<td>Mouse</td>
<td>1:100</td>
<td>R&amp;D Systems</td>
</tr>
<tr>
<td>CL203</td>
<td>ICAM-1</td>
<td>Mouse</td>
<td>1:500</td>
<td>(Verbeek et al., 1994a)</td>
</tr>
<tr>
<td>PN-1E2</td>
<td>ICAM-1</td>
<td>Mouse</td>
<td>1:25</td>
<td>(Verbeek et al., 1994a)</td>
</tr>
<tr>
<td>Pab-αB-crystallin</td>
<td>Rabbit</td>
<td>Mouse</td>
<td>1:500</td>
<td>(den Engelman et al., 2003)</td>
</tr>
<tr>
<td>1426</td>
<td>Hsp27</td>
<td>Rabbit</td>
<td>1:2000</td>
<td>Abcam</td>
</tr>
<tr>
<td>VDK-g20</td>
<td>Hsp20</td>
<td>Rabbit</td>
<td>1:4000</td>
<td>(van de Klundert et al., 1998)</td>
</tr>
<tr>
<td>J92</td>
<td>HspB8</td>
<td>Rabbit</td>
<td>1:2000</td>
<td>(Verschuere et al., 2003)</td>
</tr>
</tbody>
</table>

Expression and purification of recombinant proteins. Recombinant human αB-crystallin and HspB23 were expressed and purified as described previously (Wilhums et al., 2006a). Since it was demonstrated that HspB2 and HspB3 form functional heterogeneous complexes of 150 kDa (Sugiyama et al., 2000), both proteins were expressed together in one vector. Coding sequences for the following sHsps were ligated into the pET-46 Ek/LIC vector which also introduces a N-terminal His-tag sequence (Novagen, Merck Chemicals Ltd): human Hsp27, human Hsp20, and human HspB8. Hsp20 and HspB8 were expressed in Rosetta (DE3) pLysS competent cells (Novagen). Hsp27 was expressed in its BL21 (DE3) pLysS competent cells (Novagen). A culture inoculated from a single colony was induced by addition of 0.25 mM isopropyl-thio-β-D-galactopyranoside (IPTG) for 4 h at 37°C, with the exception of Hsp20, which was induced for 16 h at 25°C. After incubation with IPTG, cells were harvested and lysed by sonication in native lysis buffer (NLB; 50 mM NaH2PO4, 300 mM NaCl, pH 8.0) supplemented with EDTA-free protease inhibitor (Roche Applied Science). Insoluble proteins were removed by centrifugation. All sHsps were purified over a Ni-NTA agarose
column (Qiagen) using NLB supplemented with increasing concentrations of imidazole (Sigma-Aldrich Chemie BV) ranging from 20 up to 250 mM. After desalting, sHsps were concentrated in 10 mM Tris, 50 mM NaCl, pH 7.4 buffer by using an iCON concentrator spin column (Thermo Fisher Scientific Inc.). Protein concentration was determined using a BCA Protein Assay kit according to the manufacturer’s description (Thermo Fisher Scientific). Purified sHsps were aliquoted and stored at −80°C. Purity of the preparations was ≥95%.

Cell culture. Smooth muscle cells (SMCs) and astrocytes were both isolated from human brain tissue obtained after rapid autopsy, as described previously (De Groot et al., 1997; Verbeek et al., 1994b; Veerhuis et al., 1998) (Table 1). Diagnosis and grading of patients was performed according to the criteria mentioned previously. SMCs were maintained in Eagle’s modification of essential medium (EMEM; PAA Laboratories GmbH), supplemented with 10% human serum (Lonza BioWhittaker Benelux BV), 20% fetal bovine serum (PAA Laboratories GmbH), recombinant basic fibroblast growth factor (1 ng/ml) and gentamycin (2.5 µg/ml). Astrocytes were maintained in a mixture (1:1 v/v) of DMEM and Ham’s F10 supplemented with 10% fetal bovine serum, 2 mM l-glutamine (Cambrex) and gentamycin (2.5 µg/ml). All primary cell cultures were cultured at 37°C, 5% CO₂, and 90% relative humidity. Although the cultured astrocytes and SMCs were derived from different clinical backgrounds (i.e., either AD or control patients), we did not observe differences with respect to their responses in the various types of experiments.

Cell passages 3–9 were used for the experiments. Control cells incubated with EMEM or DMEM/Ham’s F10 and 0.1% BSA (serum-free medium) demonstrated normal morphology. Experiments were performed at least twice.

ELISA. Duplicate wells (12-well plate; Corning Inc) with cultured cells were preincubated with serum-free medium for a minimum of 4 h. Subsequently, cells were incubated with 12.5 µM synthetic AB₁₋₄₀, AB₁₋₄₂, or AB₁₋₄₆ or 12.5 µM purified sHsps (aβ-crystallin, Hsp27, Hsp20, HspB8 and Hspb2B3) at 37°C and 5% CO₂. This concentration was the lowest concentration to induce a significant effect across all sHsps tested. In addition, the same concentration of Aβ induced biological effects in cultured SMCs and astrocytes (Verbeek et al., 1997; Bruinsma et al., 2010) and was therefore chosen in the experiments. Lipopolysaccharide (LPS; 0.5 µg/ml; Sigma-Aldrich) stimulation (1 µg/ml) was used as a positive control for inducing cytokine production. After 48 h of incubation, supernatants and cell lysates (solubilized in RIPA; 50 mM Tris HCl, pH 7.4, 150 mM NaCl, 1% Nonidet P-40, 0.5% sodium deoxycholate, and 0.1% SDS in Milli-Q) were collected, centrifuged at 13,200 rpm for 10 min at 4°C and stored at −80°C until further use. To exclude endotoxin contamination, potentially present in the purified sHsp samples, coincubation with polymixin B (PMB; Sigma-Aldrich; 10 µg/ml) was used to inhibit LPS-mediated inflammation. In these experiments, PMB was preincubated with both the LPS and the sHsps for 1 h at 37°C before addition to the cells.

IL-8, ICAM-1, MCP-1, CD40 ligand, and TGF-β₁ levels in cell culture supernatant were measured using commercial enzyme immunoassay kits according to the manufacturer’s instructions (Duoset ELISA, R&D Systems). To correct for differences in cell density, inflammatory factor production was normalized to protein content of the cell lysate which was determined using a BCA Protein Assay kit according to the manufacturer’s description (Thermo Fisher Scientific Inc.). Concentrations of the various inflammatory factors were expressed as pg/mg protein.

Statistical analysis. Statistical analyses were performed using an independent sample t test in SPSS 14.0 for Windows software. Statistical significance was set at p < 0.05.

Results

Inflammatory cells in AD brains with severe CAA pathology, capCAA, and dyshoric angiopathy

Double staining for GFAP and Congo red demonstrated the presence of astrocytes around Aβ-laden vessels, with a more prominent GFAP staining around the larger vessels (Fig. 1A, C). Clusters of HLA-DR-positive microglia were also observed around larger vessels and capillaries laden with Aβ and were particularly prominent around the capillaries (Fig. 1B, D).

Expression of sHsps in AD brains with severe CAA pathology, capCAA, and dyshoric angiopathy

In control brains, aβ-crystallin staining was observed in glial cells (Fig. 2B). Furthermore, leptomeningeal vessels as well as a few astrocytes in the white matter were also stained (data not shown). Hsp27 staining in control brains was limited to leptomeningeal vessels (data not shown), but not observed in parenchymal vessels (Fig. 2D). Hsp20 staining in control brains was occasionally observed in astrocytes in white and gray matter (data not shown). Weak immunoreactivity of Hsp20 was also observed in large parenchymal vessels (Fig. 2F, open arrow) and leptomeningeal vessels (data not shown). Hspb8 staining in control brains was observed in astrocytes in both gray and white matter (Fig. 2H, arrow) and in cerebrovascular cells of large parenchymal vessels (Fig. 2H, open arrow). Furthermore, weak staining for HspB2 was observed in cerebrovascular cells in large parenchymal vessels (Fig. 2J, open arrow) and in an occasional astrocyte or microglial cell in the brain parenchyma (data not shown). IL-8 (Fig. 2L) and MCP-1 (Fig. 2P) staining was not observed in normal parenchymal or leptomeningeal vessels in control brains, whereas ICAM-1 staining was observed in endothelial cells in control brains (Fig. 2N, arrow).

In AD brains with severe (cap)CAA pathology, the anti-Aβ antibody (6C6) stained Aβ-affected vessels and capillaries (Fig. 3A, B). In addition, dyshoric angiopathy (Fig. 3A) was often observed. The antibodies directed against aβ-crystallin, Hsp27, Hsp20, HspB8 and HspB2 showed different staining patterns for these sHsps in CAA, capCAA and dyshoric angiopathy. Representative staining results are shown in Figure 3 and a summary of the immunohistochemical results is shown in Table 3. Anti-aβ-crystallin antibody stained reactive astrocytes and activated microglia associated with CAA (Fig. 3C) and capCAA (Fig. 3D). Hsp27 staining was not observed in gray matter (Fig. 3E, F), but was occasionally observed in reactive astrocytes and microglia in
the white matter (data not shown). In addition, reactive astrocytes surrounding CAA were immunopositive for Hsp20 (Fig. 3G) and occasionally Hsp-20-positive reactive astrocytes were observed surrounding capCAA (data not shown). Anti-HspB8 stained reactive astrocytes and microglia in both white and gray matter and occasionally immunoreactivity of HspB2 was observed with reactive astrocytes and microglia. Whereas HspB2 (Fig. 3L) colocalized with αβ in capCAA and CAA, no immunostaining for αβ-crystallin (Fig. 3C,D), Hsp27 (Fig. 3F), Hsp20 (Fig. 3G,H) and HspB8 (Fig. 3I,J) was observed. Furthermore, colocalization of Hsp20 (Fig. 3G), HspB8 (Fig. 3I) and HspB2 (Fig. 3K), but not of αβ-crystallin (Fig. 3C) and Hsp27 (Fig. 3E), with αβ surrounding CAA and capCAA (dyshoric angiopathy) was observed.

Expression of inflammatory factors in AD brains with severe CAA pathology, capCAA, and dyshoric angiopathy

ICAM-1 was associated with dyshoric αβ deposits surrounding CAA and capCAA, but not with the αβ deposits within the vessel wall (Fig. 3O,P), suggesting colocalization of Hsp20, HspB8 and HspB2 with ICAM-1 in dyshoric angiopathy near (cap)CAA. Although ICAM-1 has also been detected in a soluble form (Harning et al., 1991; Rothlein et al., 1991), it is mainly described as a membrane-bound cell adhesion molecule. Therefore, the ICAM-1 staining we observed is very likely due to membrane-bound ICAM-1. In earlier studies an increase in IL-8 and MCP-1 in AD brains was observed after soluble protein extraction of human brain lysates or in paraffin-embedded formalin-fixed tissue (Akiyama et al., 2000; Calingasan et al., 2002; Sokolova et al., 2009). In the present study, no IL-8 and MCP-1 was detectable in tissue from AD patients with severe CAA pathology (Fig. 3M,N,Q,R). In cryosections, these soluble factors might escape detection due to mild fixation of the tissue.

sHsps induce the production of inflammatory factors by human leptomeningeal smooth muscle cells and human brain astrocytes

Our immunohistochemical studies suggest that both αβ and sHsps accumulate in or near (cap)CAA, where an inflammatory reaction is observed as well. Since human leptomeningeal SMCs are already early affected by αβ in CAA (Vinters et al., 1996), we studied whether αβ or sHsps were able to induce production of cytokines and other inflammatory factors by cultured SMCs. In addition, since reactive astrocytes colocalize near (cap)CAA (Fig. 1), we also studied the potential of αβ and sHsps to induce an inflammatory reaction in human brain astrocytes.

Neither αβ_{1-40}, αβ_{1-42}, nor αβ 

Aβ_{1-42}, CD40 ligand by SMCs or astrocytes, above control levels (Figs. 4, 5). Incubation of 1 μg/ml LPS induced IL-8 production (Fig. 4A; p < 0.05) by SMCs, but not production of soluble ICAM-1 (sICAM-1; Fig. antibodies were only occasionally immunoreactive with leptomeningeal vessels (data not shown), but not with parenchymal vessels (D). Hsp20 was occasionally demonstrated in astrocytes in normal brains (data not shown). Weak immunoreactivity of Hsp20 was also observed in large parenchymal (F, open arrow) and leptomeningeal vessels. HspB8 staining was observed in astrocytes in both gray and white matter (H, arrow) and in cerebrovascular cells of large parenchymal vessels (H, open arrow). Weak staining for HspB2 was observed in cerebrovascular cells in large parenchymal vessels (J, open arrow) and in an occasional astrocyte or microglial cell in the brain parenchyma (data not shown). Furthermore, anti-IL-8 (L) and anti-MCP-1 (P) staining was absent from normal parenchymal or leptomeningeal vessels. The anti-ICAM antibodies stained endothelial cells (M, arrow). Original magnification 200×.

Figure 2. Immunohistochemical staining of αβ (A, C, E, G, I, K, M, O), sHsps (B, D, F, H, J; open arrow), and inflammatory factors (IL, N, P; open arrow) in or near normal vessels in the occipital cortex of control patients. Serial sections: A, B, C, D, E, F, G, H, I, J, K, L, N, O, P. Anti-αβ-crystallin antibodies stained glial cells throughout the cortex (B, arrow). Anti-Hsp27 stained endothelial cells (M, arrow). Original magnification 200×.
4 B), MCP-1 (Fig. 4 C) and TGF-β (Fig. 4 D). Furthermore, incubation of 1 μg/ml LPS induced IL-8 (Fig. 5 A; p < 0.01), sICAM-1 (Fig. 5 B; p < 0.01) and MCP-1 (Fig. 5 C; p < 0.05) production by astrocytes, but not production of TGF-β (Fig. 5 D) and CD40 ligand (Fig. 5 E). After preincubation and coincubation of LPS with PMB, production of inflammatory factors by SMCs and astrocytes returned to control levels (Fig. 5; p < 0.05), indicating that PMB efficiently inhibited the LPS-induced inflammatory reaction.

Incubation of SMCs with 12.5 μM Hsp20, HspB8 or HspB2B3 resulted in a strong induction of IL-8 (Fig. 4 A; p < 0.01), sICAM-1 (Fig. 4 B; Hsp20, HspB2B3, p < 0.001; HspB8, p < 0.01) and MCP-1 (Fig. 4 C; Hsp20, HspB2B3, p < 0.001; HspB8, p < 0.01) secretion, but not of TGF-β (Fig. 4 D). In contrast, preincubation with 12.5 μM Hsp27 (Fig. 4 A; p < 0.001), decreased (p < 0.01) TGF-β production was observed after Hsp27 treatment compared with control (Fig. 4 D). In addition, incubation with Hsp27 did not induce levels of sICAM-1 (Fig. 4 B) and MCP-1 (Fig. 4 C) above control levels in SMCs. Furthermore, SMCs did not seem to secrete CD40 ligand, since after incubation of these cells with either Aβ1–42, Aβ1–40 and D-Aβ1–40 or sHsps, the concentrations of CD40 ligand remained below the detection level (data not shown).

Incubation of astrocytes with 12.5 μM Hsp20, HspB8 or HspB2B3 also resulted in a strong induction of IL-8 (Fig. 5 A; p < 0.001), sICAM-1 (Fig. 5 B; p < 0.001) and MCP-1 (Fig. 5 C; p < 0.001) secretion, but not of TGF-β (Fig. 5 D). In addition, only 12.5 μM HspB8 and HspB2B3 induced CD40 ligand production by astrocytes (Fig. 5 E; p < 0.05 and p < 0.01 respectively). Comparable to the effects of Hsp27 in SMCs, IL-8 production by astrocytes was also increased after incubation with 12.5 μM Hsp27 (Fig. 5 A; p < 0.01), however, Hsp27 induced a decrease in the production of TGF-β (Fig. 5 D; p < 0.001) and CD40 ligand (Fig. 5 E; p < 0.01) compared with control. Furthermore, incubation with Hsp27 did not result in levels of sICAM-1 (Fig. 5 B) and MCP-1 (Fig. 5 C) above control levels in astrocytes.

To exclude LPS contamination, potentially present in the purified sHsp samples, we incubated cell samples with PMB and sHsps to inhibit potential LPS-mediated inflammation. After preincubation and coincubation of LPS with PMB, production of inflammatory factors by SMCs and astrocytes returned to control levels (Fig. 6 A, B; p < 0.05), indicating that PMB efficiently inhibited the LPS-induced inflammatory reaction. Whereas 12.5 μM αB-crystallin seemed to induce IL-8 secretion by SMCs and astrocytes, this effect was completely abolished by preincubation with PMB (Fig. 6 A, B; p < 0.05), indicating that traces of LPS in the αB-crystallin preparations are responsible for the observed effects. In contrast, PMB had no, or only a minimal effect, on the production levels of IL-8 by SMCs and astrocytes induced by the other sHsps samples (Fig. 6 B), suggesting a strong inducing effect of these sHsps on cytokine production.

**Discussion**

The main findings of this study are as follows: 1) Hsp20, HspB8 and HspB2 are associated with (cap)CAA and dyshoric angiopathy in AD brains with severe CAA pathology; 2) these sHsps colocalize

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**Figure 3.** Immunohistochemical staining of sHsps and inflammatory factors in or near CAA vessels (A, C, E, G, I, K, M, O, Q; serial sections) and capCAA (B, D, F, H, J, L, N, P, R; serial sections; arrows indicate the same capillary in each panel to serve as a reference to allow optimal comparison with other panels) in the occipital cortex of AD brains. The anti-Aβ antibody 6C6 stained CAA, capCAA, and dyshoric angiopathy in AD brains (A, B, to allow optimal comparison with other stains, these panels are shown twice). Both anti-αB-crystallin (C, D) and anti-Hsp27 (E, F) antibody staining was absent in Aβ deposits. No anti-Hsp20 and anti-HspB8 staining was observed in CAA and capCAA; however, colocalization of Hsp20 and HspB8 (G, H, I, J) with dyshoric angiopathy (Aβ surrounding CAA) was observed. The presence of HspB2 in CAA (K) and capCAA (L) of AD brains with severe CAA was observed, but also colocalization of HspB2 with dyshoric angiopathy (K) was observed. The anti-αB-crystallin (C, anti-Hsp20 (G), and anti-HspB8 antibodies (F) stained reactive astrocytes and microglia associated with CAA. Occasionally, immunoreactivity of HspB2 with reactive astrocytes and microglia was observed. Furthermore, anti-IL-8 (M, N, arrow) and anti-MCP-1 (Q, R, arrow) staining was absent from CAA and capCAA vessels. In addition, ICAM-1 was associated with dyshoric angiopathy, but not with the Aβ deposits in the vessel wall (D, P, arrow; inset, ICAM-1 staining (left) and Aβ staining (right) of another capCAA vessel). Original magnification 200×.

**Table 3. Summary of the immunohistochemical results**

<table>
<thead>
<tr>
<th></th>
<th>capCAA</th>
<th>CAA</th>
<th>Dyshoric angiopathy</th>
</tr>
</thead>
<tbody>
<tr>
<td>αβ-crystallin</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Hsp27</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>HspB2</td>
<td>10%</td>
<td>100%</td>
<td>90%</td>
</tr>
<tr>
<td>HspB8</td>
<td>80%</td>
<td>100%</td>
<td>95%</td>
</tr>
</tbody>
</table>

Quantification of the percentages of Aβ deposits that are stained by the sHsp antibodies in all patients (average of n = 3 patients).
In addition, colocalization of Hsp20, HspB8 and HspB2, but not Aβ, is in line with earlier studies (Richard et al., 2010; Attems et al., 2011). 

It has been suggested that especially these sHsps are important in the inflammatory reaction in AD brains than Aβ. Interestingly, the proinflammatory effect of these sHsps does not seem to be limited to a single parameter such as IL-6 (Wilhelmus et al., 2009), but includes multiple inflammatory factors that are observed in vivo. We obtained in vivo evidence for the colocalization of sHsps near sites of Aβ-associated inflammation in the cerebral vasculature and demonstrated in vitro that Hsp20, HspB8 and HspB2 induced production and secretion of IL-8, MCP-1 and sICAM-1 in SMCs and astrocytes, with little or no effect of Hsp27 and no effect of αβ-crystallin on these factors. These results are in line with, and extend, our previous findings that sHsps may be among the key mediators of the inflammatory reactions associated with (cap)CAA, since they also induced IL-6 production in cultured SMCs, astrocytes and microglia (Wilhelmus et al., 2009). Interestingly, our results suggest that those sHsps that occur extracellularly in plaques or dyshoric angiopathy and (cap)CAA (i.e., Hsp20, HspB8 and HspB2) have a potent proinflammatory effect, indicating that especially these sHsps are important in the inflammatory reaction in CAA. Interestingly, HspB8 and HspB2 induced CD40 ligand expression in astrocytes, but not in SMCs, suggesting that the reported upregulation of CD40 ligand in AD (van der Wal et al., 1993; Calingasan et al., 2002) might be due to astrocytic production. In contrast to these findings, however, Hsp20, HspB8 and HspB2 did not induce production of TGF-β1, in both SMCs and astrocytes, although these factors are also reported to be upregulated in AD (van der Wal et al., 1993; Calingasan et al., 2002). This suggests that this cytokine might be upregulated by alternative mechanisms or cell types.

Hsp27 is a member of the sHsp family with remarkable capacities compared with the other sHsps tested in this study. Hsp27 was able to induce IL-8 and inhibit TGF-β1 production in both human SMCs and astrocytes in vitro. Furthermore, Hsp27 inhibited CD40 ligand production in astrocytes. Interestingly, IL-8 is a proinflammatory cytokine and TGF-β1 can act as an anti-inflammatory factor by inhibition of local inflammation resulting in reduced tissue injury that may occur as a response to inflammation (Wahl, 1992). Furthermore, the interaction of CD40 ligand with its receptor has been implicated in the modulation of anti-inflammatory responses (Liu et al., 2010). Thus, Hsp27 may exert a proinflammatory effect, both through inducing a proinflammatory reaction (e.g., IL-8) and reducing the production of the anti-inflammatory factors (e.g., CD40 ligand and TGF-β1) (Liu et al., 2010). In addition, Hsp27 may also function with ICAM-1 in dyshoric angiopathy near (cap)CAA; 3) sHsps (especially Hsp20, HspB8 and HspB2) but not Aβ, increased secretion of IL-8, sICAM-1 and MCP-1 by cultured human leptomeningeal SMCs and human brain astrocytes; 4) Hsp27 reduced secretion of TGF-β1 by SMCs and astrocytes and CD40 ligand secretion by astrocytes.

The observed astrocytic and microglial activation, indicative of an inflammatory reaction, around (cap)CAA in this report is in line with earlier studies (Richard et al., 2010; Attems et al., 2011). In addition, colocalization of Hsp20, HspB8 and HspB2, but not αβ-crystallin and Hsp27, with (cap)CAA and dyshoric angiopathy near (cap)CAA is also in line with our previous studies in which colocalization of these sHsps was found with CAA and/or parenchymal deposits of Aβ (Wilhelmus et al., 2006b,c, 2009). It has been suggested that Hsp20, HspB8 and HspB2 are predominantly associated with fibrillar Aβ in vivo (Wilhelmus et al., 2006b,c, 2009) and our results suggest a similar association of these sHsps with fibrillar Aβ in (cap)CAA and with dyshoric angiopathy near (cap)CAA. Thus, Hsp20, HspB8 and HspB2 are clearly associated with various types of Aβ deposits in AD brains and may participate in the local inflammatory reaction.

CAA-related inflammation is of clinical importance since patients with this type of pathology present with cognitive decline, seizures and headaches, that improve upon anti-inflammatory treatment (Eng et al., 2004; Kinnekom et al., 2007; Chung et al., 2011). In addition, it has been suggested that especially capCAA with spreading of the Aβ deposits into the neuropil could contribute to a rapid clinical deterioration (Eurelings et al., 2010), suggesting an important role of capCAA and dyshoric angiopathy, rather than plaques and CAA, in cognitive decline. In AD, Aβ has been shown to trigger neuroinflammation by e.g., activation of the complement system (Heneka et al., 2010), and activation of inflammatory reactions associated with (cap)CAA, since they also induced IL-6 production in cultured SMCs, astrocytes and microglia (Wilhelmus et al., 2009). Interestingly, our results suggest that those sHsps that occur extracellularly in plaques or dyshoric angiopathy and (cap)CAA (i.e., Hsp20, HspB8 and HspB2) have a potent proinflammatory effect, indicating that especially these sHsps are important in the inflammatory reaction in CAA. Interestingly, HspB8 and HspB2 induced CD40 ligand expression in astrocytes, but not in SMCs, suggesting that the reported upregulation of CD40 ligand in AD (van der Wal et al., 1993; Calingasan et al., 2002) might be due to astrocytic production. In contrast to these findings, however, Hsp20, HspB8 and HspB2 did not induce production of TGF-β1, in both SMCs and astrocytes, although these factors are also reported to be upregulated in AD (van der Wal et al., 1993; Calingasan et al., 2002). This suggests that this cytokine might be upregulated by alternative mechanisms or cell types.

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Figure 4. Production of inflammatory factors by human brain leptomeningeal SMCs. Cultured SMCs were incubated with 12.5 μM αβ-crystallin, Aβ1–40, Aβ1–42, Hsp27, Hsp20, HspB8, HspB2, or 1 μg/ml LPS for 2 d at 37°C. Supernatant was collected and IL-8 (A), sICAM-1 (B), MCP-1 (C), and TGF-β1 (D) concentrations were measured using ELISA. Statistical analysis was performed using an independent sample t test. The level of significance of the difference compared with control is indicated as follows: *p < 0.05; **p < 0.01; ***p < 0.001; p > 0.05 is not indicated. Means ± SEM are shown.
as an indirect anti-apoptotic molecule (Concannon et al., 2003) by inhibiting the proapoptotic proteins caspase-3 (Stetler et al., 2009) and Bax (Havasi et al., 2008). Since both TGF-β1 and CD40 ligand may be involved in apoptosis during inflammation (Calingasan et al., 2002; Schuster and Krieglstein, 2002), reduced TGF-β1 and CD40 ligand levels induced by Hsp27 may add to the anti-apoptotic effect of Hsp27. Furthermore, in transgenic mice models for AD it has been demonstrated that TGF-β1 overexpression may lead to Aβ deposits in cerebral blood vessels and meningeal vessels (Wyss-Coray et al., 1997). Moreover, elevated levels of CD40 ligand may lead to endothelial dysfunction and atherothrombosis, whereas inhibition of CD40/CD40 ligand interaction may prevent atherogenesis in animal models (Urbich and Dimmeler, 2004; Chakrabarti et al., 2010; Dominguez-Rodriguez et al., 2010; Yoshioka et al., 2010). Thus, since Hsp27 affects the expression of TGF-β1 and CD40 ligand, Hsp27 may create a proinflammatory environment, likely both by reducing the production of anti-inflammatory factors and inducing production of proinflammatory cytokines, inhibit apoptotic processes and may alter the vascular micro-environment. However, more study is required to elucidate the exact role of Hsp27 in neurovascular inflammation in AD.

It has been suggested that Aβ itself can induce neuroinflammation (Heneka et al., 2010). In our study, however, Aβ1–40, Aβ1–42, and d-Aβ1–40 had no effect on the production of inflammatory factors by SMCs and astrocytes. Previously, we also demonstrated that Aβ did not induce IL-6 production by cerebrovascular cells and astrocytes (Wilhelms et al., 2009). However, in the same study it was shown that Aβ slightly induced IL-6 production by microglia (Wilhelms et al., 2009). In addition, in another study dose-dependent increases of IL-8 and MCP-1 production by human brain microglia were observed after exposure to Aβ (Lue et al., 2001). Together, these studies suggest that in the brain, microglial cells may be particularly susceptible to Aβ, resulting in an inflammatory reaction, but that other cerebral cell types, such as vascular cells and astrocytes, do not respond to Aβ in a proinflammatory way, but may be stimulated to do so by sHsps.
In conclusion, Hsp20, HspB8 and HspB2 are associated with (cap)CAA and dyshoric angiopathy in AD brains with severe CAA pathology. In addition, colocalization of these sHsps with ICAM-1 around Aβ-laden vessels was observed. Furthermore, we demonstrated that Hsp20, HspB8 and HspB2 induced the production of inflammatory factors in vitro, suggesting that these sHsps might be among the key mediators of the inflammatory reactions associated with (cap)CAA and dyshoric angiopathy. An interesting role for Hsp27 was found, since this sHsp seems to induce a proinflammatory effect by reducing the normal anti-inflammatory effect in human SMC and astrocytes in vitro. Furthermore, although it has been suggested that Aβ itself can induce inflammation (Heneka et al., 2010), we did not observe such an effect in cultured SMCs and astrocytes. The results of this study provide new insights in the inflammatory reactions associated with AD and CAA and, therefore, might provide interesting new targets for therapeutic intervention in the pathogenesis of AD and CAA.

References


