Migration-based selections of antibodies that convert bone marrow into trafficking microglia-like cells that reduce brain amyloid β

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One goal of regenerative medicine is to repair damaged tissue. This requires not only generating new cells of the proper phenotype, but also selecting for those that properly integrate into sites of injury. In our laboratory we are using a cell-migration-based in vivo selection system to generate antibodies that induce cells to both differentiate and selectively localize to different tissues. Here we describe an antibody that induces bone marrow stem cells to differentiate into microglia-like cells that traffic to the brain where they organize into typical networks. Interestingly, in the APP/PS1 Alzheimer’s disease mouse model, these induced microglia-like cells are found at sites of plaque formation and significantly reduce their number. These results raise the intriguing question as to whether one can use such antibody-induced differentiation of stem cells to essentially recapitulate embryogenesis in adults to discover cells that can regenerate damaged organ systems.

Antibody | stem cell | microglia | Alzheimer’s disease

Cell migration is central to the embryonic development and maintenance of all organisms. Despite its immense importance and much study, our knowledge of this process is still incomplete. For example, in the adult we still do not have a comprehensive understanding of which cells can migrate, where they go, and what sustains them in a differentiated state when they reach their destination.

Recently, we have developed a method that has the potential of allowing us to approach this problem. The method is based on the selection of intracellular antibodies from combinatorial libraries that modulate cell fates. One can test the effects of up to 10^8 different antibodies and, because the selection system is autocrine-based where the target and the antibody are in the same cell, each cell is a reporter system unto itself (1–9). We have previously used this method to select for antibodies that differentiate or transdifferentiate stem cells and even turn cancer cells into those with alternative phenotypes (10). Ultimately, its success is a function of the robustness of the section system. Protection from cell death, generation of a fluorescent reporter during signal transduction, or formation of a unique cellular morphology are examples of selection systems that have been used successfully (1–9). One important aspect of the method is that, once a functional antibody is found, it can then be used to identify its target, thereby giving insight into the pathway involved in the generation of the phenotype. In this respect the process is highly analogous to forward genetics except that the system and its de-convolution operate at the protein level.

We reasoned that our method should be ideal for the study of cell migration. Unlike previous selections where one must separate induced from uninduced cells, in a migration-based selection the end point of the experiment is when the cell population of interest is detected in a different location. Thus, rather than isolating phenotypically interesting cells from a mixture, one studies populations that, for physiological reasons, are enriched by self-separation. Here, we show that this method combined with adoptive transfer protocols can be used to isolate antibodies that induce hematopoietic stem cells (HSCs) from bone marrow cells to differentiate and then selectively migrate to different tissue compartments including the brain. Since the cells that migrate to the brain have many of the characteristics of microglia, we refer to them as microglia-like cells. This is because often the term “microglia” is reserved for yolk-sac-derived resident brain macrophages, and we want to avoid confusion.

If we add control of migration to the already known ability of intracellular antibodies to induce differentiation of cells, we can begin to think about reconstitution of organ systems in vivo.

Results

Selection of Antibodies in Vivo That Regulate Cell Migration. An in vivo selection scheme was developed (Fig. 1) to identify antibodies that cause differentiation of human stem cells into cell types capable of migration to specific tissues in the body, such as the brain where migratory cells are thought to be important in Alzheimer’s and Parkinson’s diseases. Genes obtained from a human single-chain fragment variable (ScFv) phage library were used to create a human ScFv lentiviral intracellular combinatorial antibody library with 10^6 unique antibody clones. In this system, the antibodies were expressed on the cell surface using a previously reported methodology (8). Total bone marrow cells were harvested from mice, infected in vitro with the lentiviral library, and then transplanted into lethally irradiated mice. After 7 d, brains of mice perfused with PBS were harvested to extract genomic DNA, which was subjected to PCR to amplify and sequence human ScFv sequences that were integrated into the genome of migrating cells. Different organs were assessed for cells that carried antibody genes from the library incorporated into their genome (Fig. S1).

The Selected Antibody Induces Migration of Cells to the Brain. As a preliminary experiment, to confirm that the integrated antibody genes induced bone marrow cells to migrate to the brain, the

Significance

A migration-based selection system is used to identify antibodies from combinatorial libraries that induce stem cells to both differentiate and selectively traffic to different tissues in adult animals. Significantly, a single agonist antibody induces microglia-like cells, which have the capacity to migrate to the brain and decrease amyloid beta deposition in the brain.

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Data deposition: Raw data from RNA-seq analyses have been deposited in the National Center for Biotechnology Information (NCBI) Gene Expression Omnibus (GEO) (ID: GSE107006).

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entire collection of antibody genes that were recovered from the
migrating cell population were cloned into lentivirus vectors,
which were then inserted into the genomes of fresh bone marrow
cells from mice expressing the red fluorescent protein (mCherry).
These donor mCherry+ bone marrow cells that then contained
the selected antibody genes were then adoptively transferred into
irradiated wild-type mice (Fig. S2). After 2 wk, brains were
perfused, harvested, and analyzed for the presence of cells
ubiquitously expressing mCherry. The brains contained many
cells expressing mCherry, indicating that at least some members
of the selected antibody population could induce cells to migrate
to the brain (Fig. S2).

To investigate whether a single antibody from this population
could induce cell migration from the bone marrow to the brain,
the B1 gene alone was cloned into a lentivirus vector that was
then used to infect total bone marrow cells freshly harvested
from mice that ubiquitously expressed the monomeric mCherry
protein. The B1 gene was selected for study because the four
antibody gene sequences that were recovered from the cells that
had migrated to the brain gave that gene the highest copy
number. Antibody B1 was seen six times in cells that migrated to
the brain but was not present in cells that migrated to other
organs (Fig. S1). In antibody selections, because the numbers of
input sequences are so high, selection of repeated sequences is of
special significance. These mCherry+ cells with the single lentivirus-
encoded B1 antibody integrated into their genome were then
transplanted into lethally irradiated wild-type mice (Fig. 2A). After
1 wk, brains were perfused and prepared for immunofluorescence histochemistry. Donor mCherry+ cells infected with lentivirus
expressing the B1 Ab migrated to the brain (Fig. 2A) and also contained
positive for the microglia marker TIMEM119 (Fig. S3A). A compre-
prehensive analysis of whole-brain sections from treated and control
mice showed that significantly more mCherry+ signal (63,270 versus
4,104 fluorescent units) was detected in the hippocampus, substantia
nigra, and hypothalamus in mice, the bone marrow of which was
infected with lentivirus encoding the B1 Ab (Fig. S3B).

We used in vivo bioluminescence imaging to confirm that the
integrated antibody genes induced bone marrow cells to migrate
to the brain. For this experiment, fresh bone marrow cells from
luciferase-expressing transgenic mice (luc+) were infected with
lentivirus encoding the B1 Ab, adoptively transferred into
irradiated wild-type mice, and imaged after 1 wk. Donor luc+ cells
infected with the B1 Ab migrated to the brain (Fig. 2B) and appear
as extensive microglia-like networks as observed in the
3D images (Fig. 2C).

Currently, it is thought that, in adoptive transfer experiments
involving irradiation, some white blood cells are able to migrate
into the brain due to a compromised blood–brain barrier (BBB)
as a result of inflammation caused by the irradiation. To study
the role of irradiation, mice were irradiated with or without a
lead helmet and analyzed 2 wk later by histochemistry. No
mCherry+ cells were seen in the brain when mice were wearing a
lead helmet during irradiation (data not shown). This result is in
agreement with the studies of others (11–13), such as Mildner
et al. (11), who showed that shielding the brain from irradiation
before adoptive transfer of cells did not lead to a significant
invasion of monocyte-derived microglia into the brain as was
observed in unshielded mice. Although we also see some mi-
gregation of bone marrow cells to the brain in control mice, it is
important to note that the efficiency was 15-fold lower than seen
with cells exposed to the agonist antibody. This enhanced effi-
ciency may be very important in a therapeutic setting where one
may want to use as many cells as possible. At any rate, the results
presented here describe a single agonist that induces microglia-
like cells, which have the capacity to migrate to the brain.

Purified Antibody Differentiates Human and Murine Stem Cells into
Microglia-Like Cells. To determine if purified antibody could
transform bone marrow cells, total mouse bone marrow or hu-
man CD34+ cells were incubated with the selected B1 Ab for
2 wk in vitro. The purified antibody induced both the mouse and
human cells to differentiate into cells with a cellular morphology
resembling microglia (Fig. 3A). To study the nature of the in-
duced cells, mRNA expression levels were analyzed for specific
oligodendrocyte, astrocyte, and microglia genes by qRT-PCR.
The cells induced by purified B1 Ab expressed mRNA for the
microglia markers CX3CR1, IBA1, CD11b, CD68, TIMEM119,
and HEXB, but failed to express mRNA for the established ol-
godendrocyte (Olig1, Olig2, and MOG) and astrocyte (GFAP,
SLC1A2, and ALDH1L1) gene markers (Fig. 3B).

RNA transcripts of human CD34+ cells treated with purified
B1 Ab were also sequenced and compared with the profile of
macrophages induced by treatment of human CD34+ cells with
macrophage colony-stimulating factor (M-CSF) in vitro. RNA
sequencing data from human CD34+ cells treated with B1 Ab or
M-CSF were consistent with qRT-PCR results. To further identify
transcripts that are expressed in microglia, we compared the results to
expression data of previous reports (14–17). Notably, we found genes
highly expressed in microglia—such as IGTM, IBA1, Trem2, APOE, CD33, ITGB2, ADORA3, GPR34, 5GFB1R, SELPL, HEXP, LTCS4, and CCL2—to be
consistent with data published by other groups (Fig. 3C and D
and Dataset S1). Importantly, we also found that B1 Ab-induced microglia
have a gene expression similar to human microglia. Among 52 genes,
the most highly expressed are from human microglia (75% of
the genes (39/52)), which is consistent with our data (Dataset S1).

To classify similarities and differences between the induced
microglia and macrophages, we compared the top 10% of trans-
cripts with the highest expression levels. Of the 3,996 total
transcripts identified, 3,098 transcripts were shared between
microglia and macrophages, 243 were unique to microglia
differentiated with B1 Ab, and 312 were unique to macrophages
differentiated with M-CSF (Fig. S4A). The most highly expressed
genes that were expressed in both microglia and macrophages
were ACPS, MMP9, APOC1, CTSL, C1QA, CTSS, CYP27A1,
and MSR1. The highly expressed genes unique to microglia in-
cluded RPL3P4, FBPI, LIF, IL9R, SIGLEC6, MARCO, UT57,
CKA4, and GPRSC6, whereas genes uniquely expressed in
macrophages included RNASE1, LAR2, FPFFB3, RNASE6, and
GPR183 (Fig. S4B and Dataset S1). Of the highly expressed genes

Fig. 1. Selection in vivo of an antibody that induces differentiation and migration of mouse HSCs. Scheme of the phenotype selection in vivo. Genes from a human ScFv phage library (10⁶ members) were cloned into a lentiviral vector to make a lentiviral intrabody library in which antibody molecules are attached to the plasma membrane and displayed on the cell surface. Total mouse bone marrow cells were infected with the antibody library in vitro and transplanted into lethally irradiated C57BL/6J mice. The system is autocrine-based because each cell has a different antibody and the putative target. After 7 d, the mouse brains were harvested and analyzed by PCR to identify any antibody genes in cells that traffic to the brain.
An agonist antibody regulates cell migration. (A) Scheme of the in vivo migration of cells from the bone marrow to the brain. From a pool of the antibody genes from all cells that had migrated to brain, a single antibody gene (B1 Ab) that was the most abundant was inserted into lentiviral vectors and used to infect total mCherry+ mouse bone marrow cells. After 3 d, these cells were transplanted into lethally irradiated wild-type C57BL/6J mice. After 1 wk, the mice were perfused with PBS followed by 2% PFA before harvesting the brains and sectioning the frozen Optimal Cutting Temperature compound blocks for immunofluorescence histochromy. Brain sections (10 μm) were stained with DAPI and anti-mCherry antibodies and then analyzed by confocal microscopy. Significantly more mCherry+ cells were identified in the treated tissues compared with controls (untreated mCherry+ cells), suggesting that mCherry+ donor cells migrated from the bone marrow to the brain. White arrows indicate microglia-like cells. (Scale bars, 50 μm.) (B) Representative images of mice that received bone marrow from luciferase-expressing transgenic mice transduced with the lentiviral B1 Ab or no Ab (control). The mice were imaged 1 wk posttransplantation. Counts in brain ROI are shown below the image. Values are the mean ± SD for n = 5 mice. (C) Showing representative sections from two different locations from brains of mice treated with B1 Ab mCherry+ cells (Left) or untreated mCherry+ cells (Right). Tissue sections were stained with DAPI (blue), for mCherry-derived bone marrow cells (red), and the antibody to the microglia marker TMEM119 (orange). The confocal 3D volume reconstructed images were obtained using IMARS software. (Scale bars, 10, 20, and 30 μm.)
specific to microglia, 268 have been reported to be relevant to neuronal diseases such as Alzheimer’s, amyloidosis, tauopathy, dementia, inflammation of the central nervous system, and encephalitis (Dataset S1).

Identification of a Novel Target. To identify the protein recognized by the B1 antibody, antibodies were produced recombinantly in Expi293F cells. Purified B1 antibody was incubated with mouse bone marrow, and immune complexes from cellular lysates were captured on a protein A/G column. Proteins that reacted with the antibody were identified by silver staining of SDS gels and mass spectrometry (MS). Three candidate proteins were identified above the background threshold (Fig. 4A). Vimentin (VIM) was one of the top hits and was confirmed to be the target antigen of the B1 Ab by Western blotting. The B1 Ab bound to purified VIM protein as well as to VIM from wild-type mouse bone marrow lysates, but did not bind to proteins in lysates from bone marrow obtained from VIM-deficient knockout mice (Fig. 4B). Bone marrow from wild-type and VIM knockout mice were incubated B1 Ab or commercial VIM Ab for 6 d. FACS analysis showed that microglia formation was increased by B1 Ab in wild-type mice. However, there was no induction of microglia in the VIM knockout mice (Fig. 4C). Interestingly, commercial VIM Ab did not induce microglia differentiation, indicating that our antibody had a unique binding mode because it was the product of selection for migration rather than simple binding (Fig. S5). Also, VIM was confirmed to be expressed on human CD34+ cells by immunofluorescence cytochemistry using B1 or commercial VIM antibodies (Fig. 4D). The amino acid sequence identity between mouse and human VIM is greater than 97%.

To determine whether binding of B1 Ab leads to the activation of signaling pathways, human CD34+ bone marrow cells were treated with the B1 Ab, and cell lysates were assessed by Western blotting with antibodies against nonphosphorylated and phosphorylated (p-) AKT, ERK, and p38. Consistent with their known role in microglia differentiation, induction of p-AKT, p-ERK, and p-p38 was observed in the cells stimulated with B1 Ab, but not with an isotype control (Fig. 4E). In addition to activation of transcription factors after binding to VIM, the B1 Ab might be expected to induce phosphorylation of VIM itself. Therefore, CD34+ cells were activated with the B1 Ab, and the resulting VIM phosphorylation was determined by Western blot using an antibody that detects phosphorylation of VIM at serine 38. The treated cells showed a marked increase in VIM phosphorylation starting at 5 min (Fig. 4F).
Fig. 4. Identification of a novel antigen recognized by the B1 Ab. (A) Cell lysates of mouse bone marrow were incubated with the B1 Ab to bind antigens. Immunoprecipitated elutes were separated by SDS/PAGE and subjected to MS analysis. Nano-LC-MS/MS analysis identified three candidate hits as potential target antigens. The VIM peptides identified by the MS data are highlighted in blue and red. (B) The B1 Ab bound to commercial VIM protein and C57BL/6J mouse bone marrow lysates in Western blots. Importantly, no protein band was observed when the B1 Ab was blotted with bone marrow lysates from VIM-deficient mice (JAX stock 025692). (C) Bone marrow from wild-type and VIM knockout mice was incubated with B1 Ab for 6 d. Cells were then stained with antimicroglia markers such as anti-TMEM119 and anti-CX3CR1. FACS analysis showed that induction of microglia in vitro was increased by B1 Ab in wild-type mice but not in VIM knockout mice, again confirming that VIM is the target of the antibody. (D) Surface expression of VIM on human CD34+ cells was confirmed by confocal microscopy using DAPI, B1 or commercial VIM antibodies, or antibody against CD34. (E and F) Human CD34+ cells were treated with B1 Ab or control isotype antibody, and cell lysates were assessed by Western blotting using antibodies against nonphosphorylated and phosphorylated (p-) AKT, ERK, p38, and VIM S38.
The Induced Microglia-Like Cells Have an Antiinflammatory M2-Like Phenotype. Polarization of the microglia is important because presumably one wants to induce those with antiinflammatory properties. To determine the nature of the microglia induced by the antibody, total mouse bone marrow cells were incubated with the selected B1 antibody for 2 wk in vitro, and specific M1/ M2 marker gene mRNA and protein expression levels were analyzed by qRT-PCR and flow cytometry, respectively. Cells treated with B1 Ab up-regulated the M2 marker genes ARG1, IL10, and CD206, whereas expression of the M1 markers iNOS, TNFα, and IL1β remained low (Fig. 5A). Furthermore, flow cytometric analysis revealed that the majority of the induced CD45<low>CD11b<+> cells stained positive for the microglial markers CX3CR1 and TMEM119 as well as the M2 markers CD36 and CD206, but negative for the M1 markers CD86 and MHCII (Fig. 5B). Together, these data suggest that the B1 Ab induced the mouse bone marrow HSCs to differentiate into microglia-like cells with M2 polarization.

The Induced Microglia-Like Cells Phagocytose the Amyloid Beta Peptide. Since microglia are important phagocytic cells in the brain, functional phagocytic and amyloid beta (Aβ) peptide aggregation assays were performed on the microglia produced from the in vitro differentiation of human CD34+ cells by the B1 Ab. The induced microglia-like cells were incubated with fluorescently labeled beads and monitored by real-time fluorescence microscopy for engulfment of beads over time. Marked phagocytosis of the beads by the induced microglia-like cells was observed and was most notable after 85 min of incubation (Fig. 5C and Fig. S6). The phagocytic cells stained positive with the mouse microglia-specific marker IBA1 after fixation at 85 min (Fig. 5C). Active phagocytosis of the beads by the microglia-like cells was also followed in a time-lapse movie (Movie S1).

While, as noted above, it was important to establish that the induced microglia-like cells are phagocytic, in the therapeutic setting of Alzheimer’s disease the extension of this phagocytic function to the Aβ peptide is of central importance. Thus, we studied the ability
Fig. 6. Bone marrow cell expressing B1 Ab protect APP/PS1 mice. (A) Plaque deposition showing a protective effect of B1 Ab treatment relative to control. Total mouse bone marrow cells were infected with lentivirus-encoded B1 Ab or untreated cells (control) and transplanted into lethally irradiated 8-wk-old APP/PS1 mice (7/group). At the 6-mo time point, significant differences between B1 Ab-treated and control mice are indicated by $$^*P < 0.005$$ (Student’s t test). (Scale bar, 1 mm.) (B) Total wild-type C57BL/6J mouse bone marrow cells were infected with lentivirus-encoded B1 Ab or untreated cells (control) and transplanted into lethally irradiated 8-wk-old APP/PS1 mice. After 2 wk (2 mo old) and 5 mo (6 mo old) post transfer, the mice were perfused with PBS, and brains were harvested and fixed in 2% PFA. Brain sections (50 μm) were stained with IBA1 for microglia and GFAP for astrocytes and analyzed by confocal microscopy. Yellow fluorescent units (Top) of IBA1 signal from brain coronal sections obtained by confocal microscopy were quantified using ImagePro software. Staining of the hippocampus with GFAP (Bottom) is shown. Red arrows indicate microglia at a higher magnification. Significant differences between B1 Ab-treated and control mice are indicated by $$^*P < 0.05$$ (Student’s t test).
of the microglia induced by the antibody to phagocytose Aβ (1–42). Indeed, the cells were strongly phagocytic for a fluorescent derivative of Aβ (Hilyte Fluor 488) (Fig. 5D).

The Induced Microglia-Like Cells Lower Aβ Deposition in the Brain. We next investigated whether this antibody could be used to lower Aβ plaques in the APP/PS1 Alzheimer’s disease mouse model, whereby the mice develop Aβ plaques and Alzheimer’s disease by 6 mo of age. The gene for the B1 antibody was inserted into the genome of fresh bone marrow cells from wild-type mice. Then these donor wild-type bone marrow cells were adoptively transferred into irradiated APP/PS1 8-wk-old mice. Brains were removed 10 d or 5 mo after adoptive transfer. The brains were perfused and prepared for immunofluorescence histochemistry. At the 6-mo time point, the brains of B1 Ab-treated mice had a significant decrease in Aβ deposition compared with control mice. Aβ deposition was 60% lower than in control mice (Fig. 6A). In addition, at the 6-mo time point, animals treated with B1 Ab had more microglia and fewer astrocytes (Fig. 6B).

Microglia-Like Cells Migrate to the Injured Brain in the Absence of Irradiation. In the studies above, brain irradiation was used to increase the efficiency of the adoptive transfer. Thus, one could argue that irradiation was also necessary for migration of microglia to the brain, and thus our studies would not be applicable to other types of brain injury such as Alzheimer’s. Therefore, we carried out studies in aged APP/PS1 mice where bone marrow transfer was carried out without irradiation. mCherry+ mouse bone marrow cells treated with B1 Ab were transplanted into nonirradiated 8-mo-old APP/PS1 mice and C57BL6 wild-type mice. After 1 wk, brain sections were stained with DAPI, IBA1, anti-mCherry, and anti-Amyloid β antibodies. mCherry+ cells from B1 Ab-treated bone marrow in these mice significantly migrated into the brains of aged APP/PS1 mouse brains compared with controls such as aged APP/PS1 mice that were not treated with B1 Ab and aged wild-type mice (Fig. 7).

Importantly, the mCherry+ cells were found adjacent to plaques in the hippocampus that already contained abundant endogenous microglia (Fig. 7). In sum, these studies suggest that the brain injury associated with Alzheimer’s disease is a permissive condition and/or driving force that allows bone marrow cells to migrate to the brain where they are found at sites of injury.

Discussion

To repair damaged tissues in the adult, one must induce cells of a desired phenotype that also properly integrate into the tissue of interest. While this might seem to be a formidable two-step event, it may be simpler if, as observed here, once certain phenotypes are induced, appropriate migration may be obligatory. This is similar to what happens in embryogenesis. Toward this end, migration-based selections from very large libraries of cells may be a powerful approach for generating those rare cells that have the appropriate phenotype as well as the ability to migrate and properly integrate into target tissues. If we can generalize these results to other systems, we may have a way to reconstitute damaged organ systems in the adult. Essentially, we want to recapitulate embryonic events. For example, one might want to find an antibody that recapitulates the embryonic events that cause cells to differentiate into insulin-producing cells that localize to islets in the pancreas.

In this study we have focused on the selection of an antibody agonist that induces bone marrow cells to differentiate into microglia-like cells that have the capacity to migrate to brain and function to reduce plaque in a murine model of Alzheimer’s disease. When selection from agnostic antibody libraries is used
to generate cells with a particular phenotype, the question invariably arises as to exactly what cell has been induced. Here, because of the consistency and diversity of the accumulated data, we can conclude that the induced cells have characteristics of microglia, which are brain resident macrophages. Indeed, the cells have the morphology of microglia, are strongly phagocytic, and contain multiple markers associated with microglia. Perhaps the strongest evidence is that the cells migrate to the brain where they form networks typical of microglia.

The identification of VIM as the target aligns with a growing body of evidence suggesting that, in addition to its more mechanical role as an intermediate filament protein involved in polar morphology, VIM also plays a role in cell attachment, migration, and cell signaling (18–20). In general, VIM is considered to be a cytoplasmic intermediate filament β-protein, but more recent evidence has shown that VIM is also located on the cell surface. For example, VIM is located on the cell surface of metastatic hepatocarcinoma cells (21) and serves as a cell-surface receptor for enterovirus 71 on a variety of cell lines (22). This surface localization is relevant to our studies using the lentivirus library to generate microglia that migrate to the brain because the antibodies are displayed on membranes of stem cells where they can bind to membrane-associated proteins on the cell (8). Moreover, we have shown that exogenous soluble antibody added to VIM filament assembly disrupts the filament network (23). Indeed, there is a certain parallelism with the role that VIM plays in the chemotactic microglia of macrophages to tissues that are sites of infection in the periphery and the putative migration of microglia to sites of brain injury (23–26). In both cases the source of the cells may be the bone marrow. It will be interesting to learn whether the injured brain generates unique chemotactic factors that direct migrating cells to sites of injury.

We do not as yet completely understand how an antibody agonist for VIM induces cell differentiation. VIM is also a scaffold for assembly and regulation of signal transduction pathways (19). For example, VIM filament assembly is required for the β2-adrenergic receptor-mediated activation of the ERK map kinase (27) and ERK-mediated epithelial–mesenchymal transition of cancer cells (28). The role of VIM in cell signaling is believed to be a consequence of its organization of signaling complexes inside the cell (19). The fact that antibody B1 induces phosphorylation of VIM is consistent with its role in signaling (29, 30). Since VIM is also on the cell surface, a similar organizing principle could account for our observation that soluble anti-VIM antibody induces cell signaling in stem cells. In this case, the antibody could either stabilize or desorb a cell surface complex involved in signal transduction. We presently are studying the nature of the members of the VIM complex on the cell surface of bone marrow cells.

An issue raised by these studies concerns whether the bone marrow is a natural site for generation of microglia. Microglia can be derived from myeloid cells of the yolk sac during embryonic and fetal development before development of the BBB and bone marrow-derived monocytic cells (BMDM) in the adult (13, 31–33). However, the key question that remains is, under what conditions do bone marrow-derived microglia-like cells migrate to the brain in adult animals? While it is now generally accepted that they migrate to the brain after injury, it is more controversial as to whether BMMDCM can cross the BBB without specific induction of brain injury. Such injury includes the irradiation damage and attendant inflammation that accompanies the generation of chimeric mice for adoptive transfer, as was used here, or for infection (31). As a practical matter, the resolution of this controversy may be mute because brain injury might be exactly when one might want to induce microglia into the brain. In a certain sense it might be beneficial if microglia migrated to sites under normal brain conditions because, when activated, these cells are not without their side effects. Therefore, selectivity based on injury might give a better therapeutic index.

As reported here, it appears that bone marrow cells can migrate to the brain and become microglia or microglia-like, but a driving force such as irradiation or inflammation is required. Autocrine migration-based selections may unearth the perhaps rare molecules involved in this driving force. As we have repeatedly shown, autocrine-based selections using membrane-bound antibodies to cytokine receptors have caused stem cells to respond and differentiate as if they had seen the natural ligand (receptor pleiotropism) (1–10). Perhaps the driving force in the present experiments is that the selected antibody provides an orthogonal activator of the brain-specific cytokine axis. Simply put, chemotactic factors from the brain may induce microglia to migrate to sites of injury in much the same way that macrophage migration is regulated in the periphery, and it is this process that is mimicked by B1 antibody (34).

Naturally, one might want to compare the therapeutic efficiency of induced microglia to antibodies against Aβ, particularly because of the mixed results seen in the extensive ongoing human trials with various Aβ antibodies. At present there is no basis for comparison, but scavenger cells might reasonably be expected to have effects that go beyond simple antibodies. Whether such effects, if any, are beneficial remains to be seen.

Materials and Methods

Mouse Strains and Cell Lines. The following mouse strains were used: C57BL/6J, FVB/NJ, B6 (Cg-J-Tyr<sup>+/–</sup> Tg (UBC-mCherry) 1Pibbz), 1295-Vim<sup>Cre</sup>-m2tm1MesDmark), FVB-Tg (CAG-luc–GFP) LG285Chcu, and B6.Cg-Tg (APPhw, PSEN1E99R5D8b/APPsw, HEK293T-765.1S) filled. The cells were then transfected with pCMVΔDHFR-MCS containing 10% FCS and penicillin and streptomycin (Gibco-Invitrogen). The Expi293F cell line was maintained in Expi293 Expression Media (Gibco-Invitrogen). Human CD34<sup>+</sup> cells (All-Cells) and mouse bone marrow cells were cultured in StemSpan serum-free media with cytokine mixture 100 (STEMCELL Technologies), only serum-free media, or RPMI 1% FBS. Mice were housed and handled according to protocols approved by the Institutional Animal Care and Use Committee at The Scripps Research Institute. According to the Scripps Office for the Protection of Research Subjects Clinical Research Services, the study is not human subject research and does not require oversight by the Scripps Institutional Review Board.

Combinatorial Antibody Library and Transduction. ScFv genes were obtained from a naive human combinatorial antibody library (1 × 10<sup>11</sup> library diversity) and subcloned into a lentiviral vector. Lentivirus was produced in HEK293T cells by cotransfection of lentiviral vectors with the pCMVΔDHFR.91 and pΟSVg viral packaging vectors at a ratio of 1:1:1. The mouse bone marrow cells were incubated with lentivirus for 3 d at 37 °C.

Bone Marrow Transplantation. Bone marrow cells were transduced with the lentiviral antibody library at a multiplicity of infection of 2 and transplanted to lethally irradiated mice. The mice with transplanted bone marrow were weaned to 1 wk to 6 mo. The brains were perfused, fixed, harvested, and kept frozen at –80 °C. The antibody genes from the brain were amplified by PCR with primer pairs customized for our lentiviral vector, analyzed by electrophoresis, and recovered.

Purification of scFv-Fc Proteins. The vector encoding the scFv-Fc tag fusion protein was transfected into Expi293F cells for transient expression. Antibodies from the pooled supernatants were purified using HITTrap Protein G HP columns with an AKTAExpress purifier (GE). The buffer was exchanged to Dulbecco’s PBS (pH 7.4) and stored at 4 °C.

Immunoprecipitation and Mass Spectrometry. For immunoprecipitation, mouse bone marrow cells were prepared and solubilized in lysis buffer. The lysates were incubated with B1 Ab for 2 h at 4 °C, followed by incubation with 50 μL of protein G-Sepharose beads (Pierce). The eluent was introduced into the linear trap quadrupole mass spectrometer from a nano-ion source with a 2-kV electrospray voltage. The analysis method consisted of a full MS scan with a range of 400–2,000 <i>m/z</i> followed by data-dependent MS/MS on the three most intense ions from the full MS scan. The raw data from the linear trap quadrupole were searched using the IPI human FASTA database with the Mascot search engine.

Western Blot. Cells were washed with PBS and then lysed in lysis buffer (50 mM Heps, pH 7.2, 150 mM NaCl, 50 mM NaF, 1 mM NaVO<sub>4</sub>, 10% glycerol, 1% Triton X-100). The lysates were then centrifuged at 12,000 × g for 15 min at 4 °C. The proteins were denatured in Laemmli sample buffer (5 min at 95 °C), separated by SDS/PAGE, and transferred to nitrocellulose membranes using
the iBlot blotting system (Invitrogen). Membranes were blocked in PBS with Tween 20 (PBST) containing 5% BSA for 30 min before being incubated with antibodies for 3 h. VIM protein (Fitzgerald) and bone marrow lysates from C57BL/6J or VIM-deficient mice were used for identification. After washing the membranes several times with PBST, the blots were incubated with 1:10 A or 1:100 BSA containing 0.2% Tween 20/PBS containing 4% horse serum and 0.2% DMSO and washed, and then incubated for 1 h with secondary antibody (goat anti-rabbit, goat anti-rat, or donkey anti-goat, 1:250; Invitrogen). Sections and coverslips were then mounted on glass slides with anti-fade mounting medium with DAPI (ThermoFisher). Confocal microscopy was performed using a Zeiss LSM 710 laser-scanning confocal microscope.

Flow Cytometry and Cell Sorting. Cells were stained with anti-mouse CD45, CD14 (eBioscience), CD86 (BD Biosciences), 111b, Cx3CR1, CD206, MHCI (Biolegend), and TMEM119 (Abcam). Stained cells were analyzed with a LSRII flow cytometer (Becton Dickinson).

Real-Time Quantitative PCR. RNA from cells cultured with B1 Ab was extracted (Qiagen) for cDNA synthesis (Bio-Rad Laboratories). PCR was performed in triplicate using 400 ng of cDNA, the RT SYBR Green supermix, and a 1:1000 Thermal cycler (Bio-Rad Laboratories). Primer sets used were specific for human Cx3CR1, Iba1, CD11b, CD68, TMEM119, HEXB, GFAP, SLC1A2, ALDH1A1, Olig1, Olig2, and MOG and for mouse ARG1, IL10, CD206, INOS, TNFα, and IL1β. Primer sequences are in Dataset S1.

Immunohistochemistry and Immunofluorescent Confocal Microscopy. Immunohistochemistry was performed on frozen whole brain sections cut transversely. Antibodies were diluted in 1x PBS containing 0.2% horse serum and 0.2% Triton-X100. Rat anti-mCherry (1:500; Invitrogen), goat anti-Cx3CR1 (1:500; R&D system), rabbit anti-Iba1 (1:500; Wako), rabbit anti-GFAP (1:500; Wako), or rabbit anti-TMEM119 (kind gift from Ben Barres, Stanford University, Stanford, CA) were used as markers for microglia. Sections were incubated overnight with primary antibody, washed, and then incubated for 1 h with secondary antibody (goat anti-rabbit, goat anti-rat, or donkey anti-goat, 1:250; Invitrogen). Sections and coverslips were then mounted on glass slides with anti-fade mounting medium with DAPI (ThermoFisher). Confocal microscopy was performed using a Zeiss LSM 710 laser-scanning confocal microscope.

Bioluminescence Imaging. Bone marrow cells from luciferase-expressing transgenic mice (mice Tg(CAG-Luc-FP) L2G82Scho) were transplanted with the lentiviral B1 Ab and transplanted into lethally irradiated recipient mice (FVB/NJ). The mice were imaged 1 wk posttransplantation. CycLuc1 (END) was injected (100 µl of 5 mM solution in PBS) i.v. into recipient mice before acquiring images using the IVIS Lumina system (Perkin-Elmer). Images were acquired as a 60-s exposure/image. Regions of interest (ROIs) were drawn around each brain, and the total number of counts within each ROI were recorded.

Phagocytosis Assay. The phagocytosis assay was conducted with DAPI-labeled Fluospheres Fluorescent Microspheres (Invitrogen). Human CD34+ cells were differentiated into microglia by the B1 Ab in a six-well plate in vitro. Microbeads were sonicated and diluted (1:80) with RPMI medium (Invitrogen) without PBS. The diluted solution was then mixed with culture medium and incubated for 2 h. To determine the phagocytic event, microglial engulfment was analyzed by an IN Cell Analyzer, 6000 (GE) during incubation at 17°C.

Aj Peptide Aggregation in Vitro. The Aj peptide aggregation assay was conducted with Beta-Amyloid (I–42) Hilyte Fluor 488-labeled (Anaspec). Human CD34+ cells were differentiated into microglia by the B1 Ab in a six-well plate in vitro. Aj peptide (20 µM) was mixed with culture medium and incubated for 12 h. The Aj peptide uptake experiment was analyzed by fluorescence microscopy (Zeiss).

Plaque Deposition Analysis. Mouse brains were perfused, fixed in 4% paraformaldehyde (PFA) for 24 h (4°C), cryoprotected with 30% sucrose in PBS (4°C), and frozen in dry ice. Serial coronal sections (50 µm thick) were collected from the genu of the corpus callosum to the caudal hippocampus. Sections (each separated by 300 µm) were stained with biotinylated HJ3.4 (Aj 1–16) antibody (gift from Jason Ulrich, Washington University in St. Louis, St. Louis) to visualize Aj-immunopositive plaques. Immunostained sections were imaged using a Leica scanner. Quantitative analysis of the percentage of area covered by HJ3.4 was performed using the ImagePro program.

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