RESEARCH ARTICLE OPEN ACCESS

Association of Brain Age, Lesion Volume, and Functional Outcome in Patients With Stroke

Sook-Lei Liew, PhD OTR/L, Nicolas Schweighofer, PhD, James H. Cole, PhD, Artemis Zavaliangos-Petropulu, PhD, Bethany P. Lo, BSc, Laura K.M. Han, PhD, Tim Hahn, PhD, Lianne Schmaal, PhD, Miranda R. Donnelly, MS, Jessica N. Jeong, BA, Zhizhuo Wang, MSc, Aisha Abdullah, BA, Jun H. Kim, BSc, Alexandre Hutton, MEng, Giuseppe Barisano, MD, PhD, Michael R. Borich, PhD, Lara A. Boyd, PhD, Amy Brodtmann, MBBS, PhD, Cathrin M. Buetefisch, MD, PhD, Winston D. Byblow, PhD, Jessica M. Cassidy, DPT, PhD, Charalambos C. Charalambous, PhD, Valentina Ciullo, PhD, Adriana Bastos Conforto, MD, PhD, Rosalia Dacosta-Aguayo, PhD, Julie A. DiCarlo, MS, Martin Domin, Dr rer med, Adrienne N. Dula, PhD, Natalia Egorova-Brumley, PhD, Wuwei Feng, MD, Fatemeh Geranmayeh, PhD, Chris M. Gregory, PhD, Colleen A. Hanlon, PhD, Kathryn Hayward, PhD, Jess A. Holguin, OTD, Brenton Hordacre, PhD, Neda Jahanshad, PhD, Steven A. Kautz, PhD, Mohamed Salah Khlif, PhD, Hosung Kim, PhD, Amy Kuceyeski, PhD, David J. Lin, MD, Jingchun Liu, MD, Martin Lotze, MD, PhD, Bradley J. MacIntosh, PhD, John L. Margetis, OTD, Maria Mataro, PhD, Feroze B. Mohamed, PhD, Emily R. Olafson, BSc, Gilsoon Park, PhD, Fabrizio Piras, PhD, Kate P. Revill, PhD, Pamela Roberts, PhD, Andrew D. Robertson, PhD, Nerses Sanossian, MD, Heidi M. Schambra, MD, Na Jin Seo, PhD, Surjo R. Soekadar, MD, Gianfranco Spalletta, MD, PhD, Cathy M. Stinear, PhD, Myriam Taga, PhD, Wai Kwong Tang, MD, Greg T. Thielman, PT, MSPT, ATC, EdD, Daniela Vecchio, PhD, Nick S. Ward, MD, Lars T. Westlye, PhD, Carolee J. Winstein, PhD, George F. Wittenberg, MD, PhD, Steven L. Wolf, PhD, Kristin A. Wong, MD, Chunshui Yu, MD, Steven C. Cramer, MD, and Paul M. Thompson, PhD

Correspondence
Dr. Liew
sliew@chan.usc.edu

Neurology® 2023;100:e2103-e2113. doi:10.1212/WNL.0000000000207219

From the Laboratory of Neuro Imaging (G.B.), Imaging Genetics Center (N.J., P.M.T.), and Department of Neurology (N. Sanossian, C.J.W.), Mark and Mary Stevens Neuroimaging and Informatics Institute (S.-L.L., J.H.K., H.K., G.P.), Keck School of Medicine, University of Southern California, Los Angeles; Chan Division of Occupational Science and Occupational Therapy (S.-L.L., B.P.L., M.R.D., J.N.J., Z.W., A.A., A.H., J.A.H., J.L.M.), Division of Biokinesiology and Physical Therapy (N. Schweighofer, C.J.W., S.-L.L.), and Herman Ostrow School of Dentistry, University of Southern California, Los Angeles; Centre for Medical Image Computing (J.H.C.), Department of Computer Science, Dementia Research Centre (J.H.C.), Queen Square Institute of Neurology, University College London, United Kingdom; Brain Mapping Center (A.Z.-P.), Department of Neurology, Geffen School of Medicine, University of California, Los Angeles; Centre for Youth Mental Health (L.K.M.H., L.S.) and Melbourne School of Psychological Sciences (N.E.-B.), University of Melbourne, Parkville, Victoria, Australia; Institute for Translational Psychiatry (T.H.), University of Münster, Germany; Department of Physical Therapy and Djavad Mowafaghian Centre for Brain Health (L.A.B.), University of British Columbia, Vancouver, Canada; The Florey Institute of Neuroscience and Mental Health (A.B., K.H., M.S.K.); Eastern Cognitive Disorders Clinic (A.B.); Royal Melbourne Hospital (A.B.), Victoria, Australia; Department of Neurology (C.M.B.) and Facility for Education and Research in Neuroscience (K.P.R.), Emory University, Atlanta, GA; Centre for Brain Research and Department of Exercise Sciences (W.D.B.), University of Auckland, New Zealand; Department of Health Sciences (J.M.C.), University of North Carolina at Chapel Hill; Department of Basic and Clinical Sciences (C.C.C.), Center for Neuroscience and Integrative Brain Research (CENIBRE) (C.C.C.), University of Nicosia Medical School, Cyprus; Laboratory of Neuropsychiatry (V.C., F.P.), IRCCS Santa Lucia Foundation, Rome, Italy; Hospital das Clínicas (A.B.C.), São Paulo University; Hospital Israelita Albert Einstein (A.B.C.), São Paulo, Brazil; Department of Psychiatry and Clinical Psychobiology (R.D.-A.), Universitat de Barcelona, Spain; Center for Neurotechnology and Neurorecovery (J.A.D., D.J.L.), Department of Neurology, Massachusetts General Hospital, Harvard Medical School, Boston; Functional Imaging Unit (M.D.), Diagnostic and Neuroradiology and Functional Imaging Unit (M.L.), Diagnostic Radiology and Neuroradiology, Universitymedicine Greifswald, Germany; Departments of Neurology (A.N.D.) and Physical Medicine & Rehabilitation (K.A.W.), Dell Medical School at The University of Texas Austin; Department of Neurology (W.F.), Duke University School of Medicine, Durham, NC; Clinical Language and Cognition (CLC) Lab (F.G.), Department of Brain Sciences, Imperial College London, United Kingdom; Department of Health Sciences & Research (C.M.G., S.A.K.), Medical University of South Carolina, Charleston; Cancer Biology (C.A.H.), Wake Forest School of Medicine, Winston Salem, NC; Innovation, Implementation and Clinical Translation (IIMPACT) in Health (B.H.), Allied Health and Human Performance, University of South Australia, Adelaide; Ralph H. Johnson VA Medical Center (S.A.K., N.J.S.), Charleston, SC; Department of Radiology (A.K., E.R.O.), Weill Cornell Medicine, New York, NY; Department of Radiology (J.L., C.Y.), Tianjin Medical University General Hospital, China; Hurvitz Brain Sciences Program (B.J.M.), Centre for Brain Resilience & Recovery and Canadian Partnership for Stroke Recovery (A.D.R.), Sunnybrook Research Institute, Toronto, Ontario, Canada; Computational Radiology Artificial Intelligence Unit (B.J.M.) and Norwegian Centre for Mental Disorders Research (NORMENT) (L.T.W.), Department of Mental Health and Addiction, Oslo University Hospital, Norway; Department of Clinical Psychology and Psychobiology (M.M.), and Institut de Neurociències (M.M.), University of Barcelona; Institut de Recerca Pediàtrica (M.M.), Hospital Sant Joan de Déu, Esplugues de Llobregat, Spain; Jefferson Integrated MRI Center (F.B.M.), Department of Radiology, Thomas Jefferson University, Philadelphia, PA; Cedars-Sinai (P.R.), Los Angeles, CA; California Rehabilitation Institute (P.R., S.C.C.), Los Angeles; Department of Kinesiology and Health Sciences (A.D.R.), University of Waterloo, Ontario, Canada; Department of Neurology (H.M.S., M.T.), NYU Langone, New York; Department of Rehabilitation Sciences (N.J.S.), and Department of Health Sciences and Research (N.J.S.), Medical University of South Carolina, Charleston; Department of Psychiatry and Neurosciences (S.R.S.), Clinical Neurotechnology Laboratory, Charité–Universitätsmedizin Berlin, Germany; Laboratory of Neuropsychiatry (G.S.), IRCCS Santa Lucia Foundation, Rome, Italy; Division of Neuropsychiatry (G.S.), Department of Psychiatry and Behavioral Sciences, Baylor College of Medicine, Houston, TX; Department of Medicine (C.M.S.), University of Auckland, New Zealand; Department of Psychiatry (W.K.T.), Faculty of Medicine, The Chinese University of Hong Kong; Department of Physical Therapy and Neuroscience (G.T.T.), University of the Sciences, Philadelphia, PA; Department of Clinical and Behavioral Neurology (D.V.), IRCCS Santa Lucia Foundation, Rome, Italy; UCL Queen Square Institute of Neurology (N.S.W.), London, United Kingdom; Department of Psychology (L.T.W.), University of Oslo, Norway; Department of Neurology & RNEL (G.F.W.), University of Pittsburgh; GRECC/HERL (G.F.W.), VA Pittsburgh Healthcare System, PA; Department of Rehabilitation Medicine Division of Physical Therapy (M.R.B., S.L.W.), Department of Rehabilitation Medicine, Division of Geriatric Medicine (S.L.W.), Department of Medicine, and Department of Cell Biology (S.L.W.), Emory University School of Medicine; Center for Visual and Neurocognitive Rehabilitation (S.L.W.), Atlanta VA Health Care System, GA; and Department of Neurology (S.C.C.), University of California, Los Angeles. Giuseppe Barisano is currently at the department of Neurosurgery, Stanford Medicine, Stanford University, CA; Kathryn Hayward is currently at the departments of Physiotherapy and Medicine (RMH), University of Melbourne, Parkville, Victoria, Australia; and Gregory T. Thielman is currently at Physical Therapy and Neuroscience, School of Health Professions, Saint Joseph's University, Philadelphia, PA.

Go to Neurology.org/N for full disclosures. Funding information and disclosures deemed relevant by the authors, if any, are provided at the end of the article.

Glossary

brain-PAD = brain-predicted age difference; **CST-LL** = corticospinal tract lesion load; **FMA-UE** = Fugl-Meyer Assessment for upper extremity; **ICV** = intracranial volume; **IQR** = interquartile range; **NIHSS** = NIH Stroke Scale; **OR** = odds ratio.

Abstract

Background and Objectives

Functional outcomes after stroke are strongly related to focal injury measures. However, the role of global brain health is less clear. In this study, we examined the impact of brain age, a measure of neurobiological aging derived from whole-brain structural neuroimaging, on poststroke outcomes, with a focus on sensorimotor performance. We hypothesized that more lesion damage would result in older brain age, which would in turn be associated with poorer outcomes. Related, we expected that brain age would mediate the relationship between lesion damage and outcomes. Finally, we hypothesized that structural brain resilience, which we define in the context of stroke as younger brain age given matched lesion damage, would differentiate people with good vs poor outcomes.

Methods

We conducted a cross-sectional observational study using a multisite dataset of 3-dimensional brain structural MRIs and clinical measures from the ENIGMA Stroke Recovery. Brain age was calculated from 77 neuroanatomical features using a ridge regression model trained and validated on 4,314 healthy controls. We performed a 3-step mediation analysis with robust mixed-effects linear regression models to examine relationships between brain age, lesion damage, and stroke outcomes. We used propensity score matching and logistic regression to examine whether brain resilience predicts good vs poor outcomes in patients with matched lesion damage.

Results

We examined 963 patients across 38 cohorts. Greater lesion damage was associated with older brain age ($\beta = 0.21$; 95% CI 0.04–0.38, $p = 0.015$), which in turn was associated with poorer outcomes, both in the sensorimotor domain ($\beta = -0.28$; 95% CI −0.41 to −0.15, $p < 0.001$) and across multiple domains of function ($\beta = -0.14$; 95% CI −0.22 to −0.06, $p < 0.001$). Brain age mediated 15% of the impact of lesion damage on sensorimotor performance (95% CI 3%–58%, $p = 0.01$). Greater brain resilience explained why people have better outcomes, given matched lesion damage (odds ratio 1.04, 95% CI 1.01–1.08, $p = 0.004$).

Discussion

We provide evidence that younger brain age is associated with superior poststroke outcomes and modifies the impact of focal damage. The inclusion of imaging-based assessments of brain age and brain resilience may improve the prediction of poststroke outcomes compared with focal injury measures alone, opening new possibilities for potential therapeutic targets.

A critical topic in stroke research is understanding why some patients demonstrate better outcomes than others, despite similar amounts of lesion damage. To address this question, research has traditionally focused on 2 spatial levels of brain injury: the focal level (i.e., the lesion and how it injures individual brain structures, such as the corticospinal tract[1-4]) and the network level (i.e., how brain structures that are functionally or structurally connected to the lesioned area but distant from the injury are nonetheless affected, e.g., through diaschisis[5-7]). However, a third level has also recently begun to garner attention in stroke research: global brain health, which represents the cellular, vascular, and structural integrity of the entire brain. The integrity of residual brain tissue may be critical for neural plasticity after stroke.[8,9] Acute stroke studies show that early measures of poor brain health, such as atrophy, markers of white matter disease, and prior infarcts throughout the brain, are associated with poorer outcomes on the modified Rankin scale and cognition at 90 days,[10] while better structural integrity is associated with better modified Rankin scores.[11] However, little attention has been given to the role of global brain health in chronic stroke or in relation to domain-specific rehabilitation outcomes,[12] such as sensorimotor impairment.

In this study, we specifically focused on a measure of global brain health known as brain age, a neurobiological construct derived from whole-brain structural neuroimaging.[13,14] To calculate brain age, a machine learning algorithm is trained to associate chronological age with neuroimaging-based indices of interest (e.g., patterns of whole-brain structural integrity from regional thickness, surface area, and volumes). The trained model is then used to predict brain age in new individuals. A higher brain-predicted age difference (brain-PAD), calculated as the difference between a person's predicted brain age minus their chronological age, suggests that the brain appears to be older than the person's chronological age. An

older-appearing brain has been associated with different disease states, including Alzheimer disease,[15] major depression,[16] and traumatic brain injury,[17] and with an increased risk of mortality[14] and more severe disease progression[18,19] However, brain age has not been widely explored in stroke. Two studies have demonstrated that brain-PAD is higher after stroke compared with that in healthy controls[20] and reliable across time.[21] However, no associations have been reported between brain age and either infarct volume or poststroke sensorimotor outcomes.

Beyond brain age, we also examine the concept of structural brain resilience, which we define in the context of stroke as the maintenance of structural whole brain integrity, measured as younger brain age, despite matched lesion damage. This concept draws upon research on cognitive resilience in "super agers" or older adults who demonstrate exceptional cognitive performance despite their advanced age.[22] These individuals are believed to demonstrate biological resilience to traditional aging pathways (e.g., identified through neuroimaging, genetic, or histologic profiles) compared with their peers.[22,23] However, while cognitive resilience refers to maintained behavioral performance despite common age-related neurologic changes, in this study, we aimed to study maintained brain structural integrity despite matched focal injury. We suggest that greater brain resilience to focal lesion damage should result in younger-appearing brains, while less brain resilience should make the brain more vulnerable to widespread degeneration after the same amount of injury and manifest as older-appearing brains, with subsequent changes in behavior.

Using subsets of the data, we tested the following 4 hypotheses: First, we hypothesized that more lesion damage and longer time since stroke should be related to higher brain-PAD, which may reflect loss of structural integrity due to poststroke secondary atrophy. Second, we hypothesized that a higher brain-PAD would be associated with worse sensorimotor outcomes and worse global outcomes across multiple functional domains due to less residual brain tissue available to support neuroplastic changes required for recovery. We anticipated that this relationship would be strongest in the ipsilesional hemisphere, which should undergo more changes with functional relevance compared with the contralesional hemisphere, and in chronic stroke, allowing for time after stroke for secondary atrophy to occur.[24-26] Third, we hypothesized that brain-PAD would mediate the impact of known focal injury measures, such as corticospinal tract lesion load (CST-LL),[1-3] on sensorimotor outcomes and that this relationship would again be strongest in the ipsilesional hemisphere in chronic stroke. Finally, we hypothesized that greater brain resilience despite stroke-related injury would distinguish people with better vs worse sensorimotor outcomes. That is, given the same amount of focal brain damage, we expected people with less global brain damage, as indexed by lower brain-PAD, to have better outcomes than people with more global brain damage.

Methods

Study Design and Patients

Cross-sectional multisite data were pooled from the ENIGMA Stroke Recovery Working Group and frozen for this analysis on January 24, 2022. A full description of the data and procedures used by the ENIGMA Stroke Recovery Working Group has been reported elsewhere (see also eMethods, links.lww.com/WNL/C720).[24,27] In brief, stroke neuroimaging and behavioral data from retrospective studies are contained in a repository, which is queried to extract data meeting study-specific eligibility criteria. For this study, we extracted data that had the following: (1) FreeSurfer outputs from 3-dimensional T1-weighted structural brain MRI volumes (see MRI Data Analysis), (2) a sensorimotor behavioral outcome measure (see Behavioral Data), (3) covariates of age and sex, and (4) a primary stroke reported in either cerebral hemisphere. Some analyses used subsets of this data with specific characteristics (e.g., early stroke [≤6 weeks poststroke] vs chronic stroke [≥180 days poststroke] or manually segmented lesion masks to extract focal injury metrics [see Lesion Analysis]). See eMethods and eFigure 1 for more information about subanalyses.

Standard Protocol Approvals, Registrations, and Patient Consents

All data were collected in accordance with the Declaration of Helsinki and in compliance with local ethics boards at each respective institute. Written informed consent was obtained from all participants in the study. Approval was received from the University of Southern California Health Science Campus Institutional Review Board (IRB No. 00002881) to conduct this study.

MRI Data Analysis

Brain Age Analysis

As previously detailed,[24,27] MRI data from each cohort were visually inspected on receipt for quality control and again after each processing step. The brain imaging software FreeSurfer (version 5.3) was used to automatically segment the T1-weighted MRIs. Subsequently 153 features of interest were extracted: 68 measures of cortical thickness, 68 measures of cortical surface area, 14 measures of subcortical volume, 2 lateral ventricle volumes, and the total intracranial volume (ICV). Left and right hemisphere features were then averaged, resulting in a total of 77 features of interest.

We calculated predicted brain age using a previously published ridge regression model trained on a cohort of 4,314 healthy controls between 18 and 75 years of age.[16] Although there are many excellent methods for defining brain age, we specifically selected this model because it was developed on multisite retrospective data collected from 19 cohorts from different countries, similar to our multisite dataset. In addition, this model is publicly available, allowing for greater scientific reproducibility (photon-ai.com/enigma_brainage). The model requires tabular data from FreeSurfer outputs

(i.e., the 77 features of interest described earlier), rather than raw image data. Following Han et al.,[16] we estimated brain age using separate models for males and female individuals. We then calculated brain-PAD by subtracting chronological age from predicted brain age:

$$\text{Brain PAD} = \text{predicted brain age} - \text{chronological age}$$

Brain age was derived from the mean of both hemispheres for all analyses, except for ipsilesional vs contralesional brain age analyses, which were derived from only ipsilesional or only contralesional brain measures. Because lesioned tissue could have affected brain age estimation, we also included lesion volume and corticospinal tract lesion load in the models to account for the possible confounding effect of lesion damage on brain age (see eMethods, links.lww.com/WNL/C720 for more information on quality control and model performance metrics).

Lesion Analyses

In a subset of the data for which we received raw T1-weighted MRIs and could identify observable lesions, lesion masks were manually segmented by trained research team members based on a previously published lesion segmentation protocol.[28,29] Lesions were preprocessed with intensity nonuniformity correction, intensity standardization, and registration to the MNI-152 template, as previously detailed.[29] Lesion volume (measured in voxels) and percent of CST-LL, or overlap, were calculated using the open-source Pipeline for Analyzing Lesions after Stroke toolbox.[30] We used a publicly available CST template that includes origins from both primary and higher-order sensorimotor regions,[31] which was found to be more strongly associated with poststroke sensorimotor impairment than a CST template derived from primary motor cortex alone.[1]

Behavioral Data Analysis

We harmonized different behavioral measures collected across cohorts by defining a primary sensorimotor outcome score, which was the percentage of the maximum possible score each individual achieved, as previously performed[24] (eMethods, links.lww.com/WNL/C720). This resulted in a score where 100 indicated no impairment and 0 indicated severe impairment. We also examined a single measure of sensorimotor impairment (Fugl-Meyer Assessment for upper extremity [FMA-UE]) and a single measure of global stroke severity across several domains (e.g., sensorimotor, language, and cognitive deficits; the NIH Stroke Scale [NIHSS]; eMethods),[32] in subsets of the data with these specific measures. Given the associations of brain-PAD with many different clinical disease states, we expected brain-PAD to be related to all functional outcome measures.

Statistical Analysis

We used a 1-way analysis of variance to examine differences between the standard brain age prediction calculated from the mean of both hemispheres, from the ipsilesional hemisphere only and from the contralesional hemisphere only. We used robust linear mixed-effects regression models to examine associations between brain-PAD, sensorimotor outcomes, and lesion damage. Full methodological details can be found in the eMethods (links.lww.com/WNL/C720).

We performed a mediation analysis using a 3-step segmentation approach.[33,34] In this analysis, we examined the following: (1) the effect of the independent variable (lesion damage) on the mediator (brain-PAD), (2) the effect of the mediator (brain-PAD) on sensorimotor outcomes, and (3) the mediation effects of brain-PAD on the relationship between lesion damage and sensorimotor outcome.

In the first step, we tested whether CST-LL influenced brain-PAD. We included covariates of lesion volume, age, sex, ICV, and days poststroke as fixed effects and cohort as a random effect.

In the second step, we examined whether brain-PAD affected sensorimotor impairment, with covariates of age, sex, and ICV and a random effect of cohort. We also examined whether this relationship was maintained when looking specifically at sensorimotor impairment in a subset of participants with the FMA-UE and in a subset with a multidomain measure (the NIHSS; eMethods, links.lww.com/WNL/C720). We further hypothesized that if this brain-behavior relationship is reflective of poststroke atrophy, it should be strongest in the ipsilesional hemisphere in chronic stroke. We therefore examined ipsilesional vs contralesional brain-PAD separately and at 2 different times poststroke, as in our previous work[24] (early stroke (≤6 weeks poststroke, believed to represent the premorbid brain before secondary degeneration)[20] and chronic stroke [≥180 days poststroke]).

In the last step, we performed a mediation analysis to examine whether brain-PAD mediates the impact of CST-LL on sensorimotor outcomes. We tested the significance of the indirect effect using bootstrapping procedures. Unstandardized indirect effects were computed for 5,000 bootstrapped samples, and the 95% CI was computed by determining the indirect effects at the 2.5th and 97.5th percentiles (eMethods, links.lww.com/WNL/C720). As part of the mediation analysis, we replicated the previously shown relationship between CST-LL and sensorimotor outcomes.[1-3] To further explore the relationship between brain-PAD and CST-LL, we also performed a supplemental regression analysis to test whether there is an interaction between these 2 factors on sensorimotor outcomes (eMethods).

Finally, we examined whether structural brain resilience explains why some people have better vs worse outcomes, despite the same amount of lesion damage. We operationally defined structural brain resilience as lower brain-PAD (younger brain age) despite equal amounts of lesion damage (both CST-LL and lesion volume), which we expected to be associated with better outcomes. We used logistic regression to test whether brain-PAD could distinguish those

Table 1 Summary of Research Cohort Characteristics

Cohort ID	Country	n	Age	Sex (F/M)	Median sensorimotor score
1	United States	34	60 (16, 31–75)	10/24	65.2 (23.5, 0–88)
2	United States	11	68 (13, 39–74)	5/6	53.0 (43.2, 20–73)
3	United States	12	58 (16, 33–71)	5/7	26.5 (30.3, 8–61)
4	Germany	17	44 (14, 30–68)	5/12	14.4 (16.7, 2–51)
5	United States	25	63 (12, 44–75)	11/14	81.8 (40.9, 21–100)
7	UK	38	56 (14, 18–75)	12/26	86.0 (31.6, 37–100)
8	United States	8	62 (10, 39–75)	2/6	55.0 (35.0, 0–100)
9	Norway	80	68 (17, 24–75)	26/54	100.0 (6.4, 57–100)
10	China	24	59 (13, 42–74)	5/19	100.0 (1.5, 68–100)
11	China	29	57 (11, 44–71)	10/19	100.0 (4.5, 9–100)
12	New Zealand	37	66 (18, 31–74)	18/19	66.7 (71.2, 3–97)
13	New Zealand	33	64 (19, 33–75)	12/21	21.2 (37.9, 3–97)
15	United States	14	57 (11, 45–74)	6/8	72.0 (24.6, 38–83)
17	United States	16	59 (4, 45–68)	5/11	54.5 (22.7, 23–74)
18	United States	11	59 (7, 46–73)	5/6	65.2 (22.0, 53–89)
19	Germany	13	62 (21, 33–74)	3/10	84.0 (8.0, 77–92)
20	Germany	18	64 (12, 49–75)	7/11	89.0 (8.8, 71–100)
21	Germany	8	62 (23, 40–75)	1/7	91.6 (13.1, 60–100)
22	Germany	17	59 (30, 25–72)	4/13	62.5 (50.0, 0–81)
23	United States	10	57 (10, 31–64)	6/4	38.6 (18.6, 27–79)
24	United States	18	62 (11, 32–72)	10/8	95.0 (0.0, 60–95)
25	Canada	22	60 (17, 37–75)	9/13	93.5 (39.8, 0–100)
27	United States	27	56 (9, 37–68)	7/20	28.2 (18.0, 0–57)
28	United States	26	62 (11, 23–75)	7/19	75.0 (24.6, 35–100)
31	United States	31	57 (9, 21–74)	8/23	51.5 (35.6, 20–91)
34	United States	14	58 (13, 32–65)	6/8	82.6 (21.2, 58–95)
35	Brazil	14	63 (18, 31–75)	6/8	70.5 (44.7, 15–94)
38	Italy	68	63 (20, 30–75)	27/41	92.5 (46.3, 0–100)
40	Italy	31	62 (20, 27–75)	16/15	65.0 (42.5, 10–100)
41	Australia	58	65 (10, 32–75)	23/35	100.0 (4.2, 83–100)
42	Brazil	29	48 (15, 25–75)	15/14	62.0 (20.0, 21–80)
46	United States	6	62 (6, 51–63)	1/5	43.9 (16.7, 27–91)
47	Australia	39	64 (10, 43–75)	12/27	65.2 (34.8, 6–98)
48	Canada	31	67 (14, 37–75)	12/19	75.8 (43.9, 0–100)
49	United States	8	62 (15, 37–71)	5/3	95.2 (1.2, 90–100)
52	United States	28	60 (14, 34–74)	11/17	43.2 (9.1, 21–52)
53	UK	48	61 (17, 26–75)	19/29	90.5 (19.6, 38–100)
54	United States	10	64 (10, 51–72)	4/6	40.2 (78.4, 3–100)

Age and sensorimotor score are shown as the median for each cohort, with the interquartile range and range (minimum–maximum) shown in parentheses.

with better vs worse outcomes, after matching for the extent of focal lesion damage between groups. As previously published guidelines for the FMA-UE established cutoffs for mild vs severe impairment at above 42 and below 27 points, respectively (corresponding to sensorimotor scores of 63.6% and 40.9%, respectively).[35] Because our dataset is composed of the FMA-UE along with other sensorimotor measures, we adapted this guideline by dividing the data into the top and bottom thirds (roughly corresponding to the FMA-UE cutoffs) to represent good vs poor outcomes, respectively. We matched the groups on both lesion damage to the corticospinal tract (CST-LL) and extent of lesion damage (lesion volume), using 1:1 nearest-neighbor propensity score matching without replacement and a stringent caliper of 0.05 standard deviations of the propensity score.[36] We estimated propensity score using logistic regression of the outcome on the covariates of CST-LL and lesion volume. We then used logistic regression on the matched dataset to predict better vs worse outcomes as a binary variable, with brain-PAD as the primary predictor and covariates of age, sex, ICV, and cohort.

All statistical analyses were run in R (version 3.6.3; R Core Team, 2020)[37]; see the eMethods (links.lww.com/WNL/C720) for the full list of libraries. For all analyses, we summarize β coefficients for predictors, along with the sample size (n), *t* value, SE, degrees of freedom (*df*), 95% CI, and *p* value in tables.

Data Availability

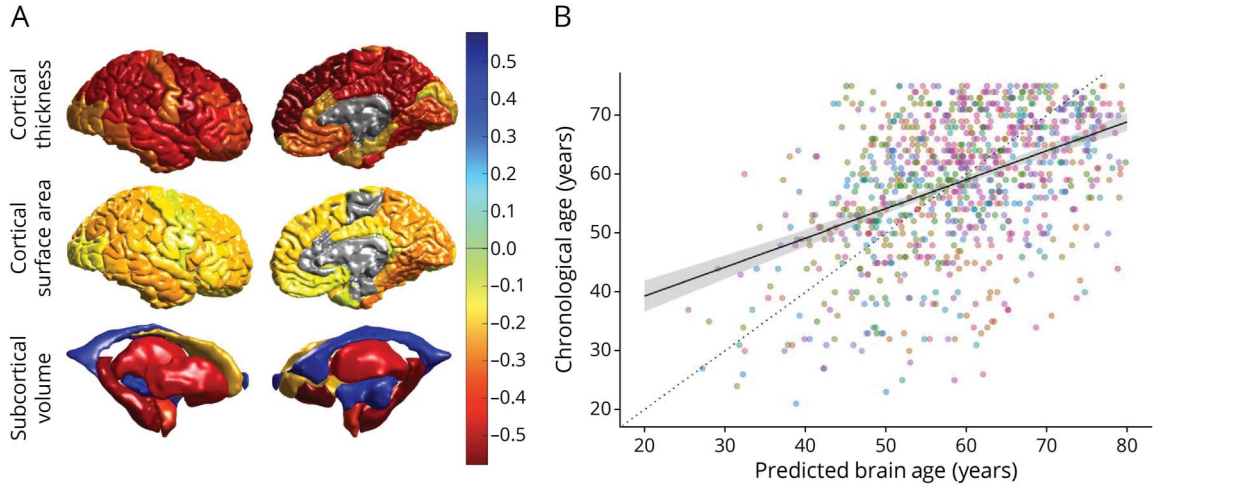
The brain age model[16] can be freely accessed from photon-ai.com/enigma_brainage, and code for extracting FreeSurfer features of interest and formatting them for brain age analyses can be from github.com/npnl/ENIGMA-Wrapper-Scripts. The CST region of interest atlas[31] can be freely accessed from lrnlab.org/. Our T1-weighted MRI data and accompanying lesion masks are publicly available here[29]: fcon_1000.projects.nitrc.org/indi/retro/atlas.html. Additional summary data and code from this study are available upon reasonable request from the corresponding author (see eMethods, links.lww.com/WNL/C720).

Results

As of January 24, 2022, the ENIGMA Stroke Recovery Working Group[27] dataset contained data from 1,221 patients. Cross-sectional data from 963 individuals with stroke from 38 cohorts across 10 countries met the current eligibility criteria and were included in this analysis (Table 1; eTable 1, links.lww.com/WNL/C720). There were 607 male and 356 female patients, with a median age of 61 years (interquartile range [IQR] 16 years). Stroke severity (i.e., primary sensorimotor score) ranged from 0 to 100 (median 78.46, IQR 49.78). Chronicity ranged from 1 to 7,439 days (median 244 days, IQR 875 days). Data were collected early after stroke (≤6 weeks) in 205 participants and in the chronic stage (≥180 days) in 558 participants. Lesion volume ranged from 0.013 to 294.80 mL (median 6.38 mL, IQR 3.47 mL). A probabilistic lesion overlap map can be found in eFigure 2.

Older predicted brain age was associated with older chronological age and larger ventricle volumes and was correlated with smaller regional cortical thickness, cortical surface area, and subcortical volume measures (Figure 1; eResults). Ipsilesional brain-PAD was significantly higher than brain-PAD calculated from the mean of both hemispheres, while

Figure 1 Brain Age Associations in People With Stroke



(A) Visualization of correlations between predicted brain age and region-of-interest measurements (top: cortical thickness, middle: cortical surface area, bottom: subcortical volumes). Warmer colors indicate stronger negative associations (e.g., larger volumes are associated with younger predicted brain age), while cooler colors indicate stronger positive associations (e.g., larger ventricles are associated with older predicted brain age). (B) Chronological age by predicted brain age across the entire sample. The identity line (dotted) and fixed-effects model regression line (solid) are displayed with SE in gray shading; different research cohorts are indicated by color.

Table 2 Relationship Between Poststroke Sensorimotor Outcomes and Brain-PAD

	Whole cohort N = 963, R^2 = 0.596				Ipsilesional brain age N = 950, R^2 = 0.589				Chronic stroke only N = 558, R^2 = 0.592			
Predictors	**β**	**SE**	**95% CI**	***p* Value**	**β**	**SE**	**95% CI**	***p* Value**	**β**	**SE**	**95% CI**	***p* Value**
Brain-PAD	**−0.28**	**0.07**	**−0.41 to −0.15**	**<0.001**	**−0.30**	**0.05**	**−0.41 to −0.20**	**<0.001**	**−0.26**	**0.09**	**−0.43 to −0.10**	**0.002**
Age	−0.05	0.06	−0.17 to 0.08	0.462	−0.07	0.06	−0.19 to 0.06	0.299	0.01	0.09	−0.16 to 0.19	0.886
Sex	**3.40**	**1.55**	**0.37 to 6.43**	**0.028**	2.93	1.55	−0.10 to 5.96	0.058	2.83	2.01	−1.11 to 6.77	0.159
ICV	−0.61	0.78	−2.14 to 0.92	0.437	−0.35	0.78	−1.88 to 1.17	0.651	−0.99	1.01	−2.98 to 1.00	0.330

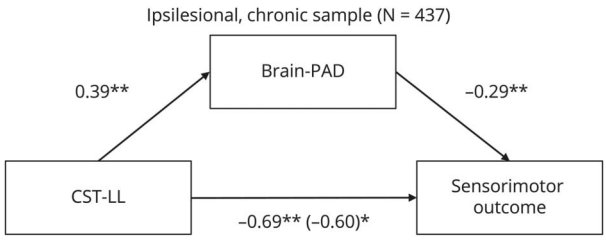
Abbreviations: brain-PAD = brain-predicted age difference; ICV = intracranial volume.
Summary statistics from robust mixed-effects linear regression to test associations between overall sensorimotor score and brain-PAD (left), brain-PAD derived only from the ipsilesional hemisphere (middle), and brain-PAD in chronic stroke only (right). Sex is coded as a factor (females = 0, males = 1). The sample size (n), conditional R^2, β, SE, 95% CI, and *p* value for all fixed-effect covariates are reported. Significant predictors are denoted in bold.

contralesional brain-PAD was significantly lower ($F(2,2802) = 53.69$, $p < 0.001$).

Higher Brain-PAD Occurs With More Lesion Damage and Longer Time After Stroke

In the first step of our 3-step mediation analysis, we examined the effect of the independent variable (lesion damage) on the mediator (brain-PAD). We tested our first hypothesis that brain-PAD is larger when there is more lesion damage and longer time since stroke. Using a subset of data with lesion metrics and days since stroke (n = 639), we found that both CST-LL ($\beta = 0.21$, $p = 0.015$) and lesion volume ($\beta = 2.83$, $p < 0.001$) were positively associated with brain-PAD, such that more CST-LL and larger lesions resulted in higher brain-PAD (eTable 2, links.lww.com/WNL/C720). Longer time poststroke (e.g., more chronic stroke) was significantly associated with a higher brain-PAD ($\beta = 1.14$, $p = 0.026$). Age was negatively correlated with brain-PAD ($\beta = -0.53$, $p < 0.001$), such that younger adults showed a higher brain-PAD. This was anticipated due to a known regression dilution effect,[38] in which younger samples are predicted to be older and older samples are predicted to be younger due to a regression toward the mean; this is a key reason why chronological age is included as a covariate (see eMethods).

Figure 2 Brain-PAD Mediates the Effects of CST-LL on Sensorimotor Outcome



The effects of CST-LL on sensorimotor outcome, as mediated by brain-PAD, are depicted in the chronic stroke sample using ipsilesional brain-PAD. The mediated effect of CST-LL is shown in the bottom parenthesis. Significance values are denoted as follows: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. brain-PAD = brain-predicted age difference; CST-LL = corticospinal tract lesion load.

Poorer Sensorimotor Outcomes Are Associated With a Higher Brain-PAD

In the second step of our mediation analysis, we examined whether the mediator (brain-PAD) influences the dependent variable (post-stroke outcomes), testing our second hypothesis that a higher brain-PAD would be associated with worse outcomes. Across the entire cohort (n = 963), a higher brain-PAD was associated with worse sensorimotor outcomes ($\beta = -0.28$, $p < 0.001$; Table 2). There was also an association with sex ($\beta = 3.40$, $p = 0.028$), with female patients demonstrating worse sensorimotor behavior than male patients. The brain age relationship was also maintained when examining a specific measure of sensorimotor impairment (FMA-UE; n = 528; $\beta = -0.30$, $p = 0.004$) and a multidomain measure of stroke severity (NIHSS; n = 238, $\beta = -0.14$, $p < 0.001$; eTable 3, links.lww.com/WNL/C720).

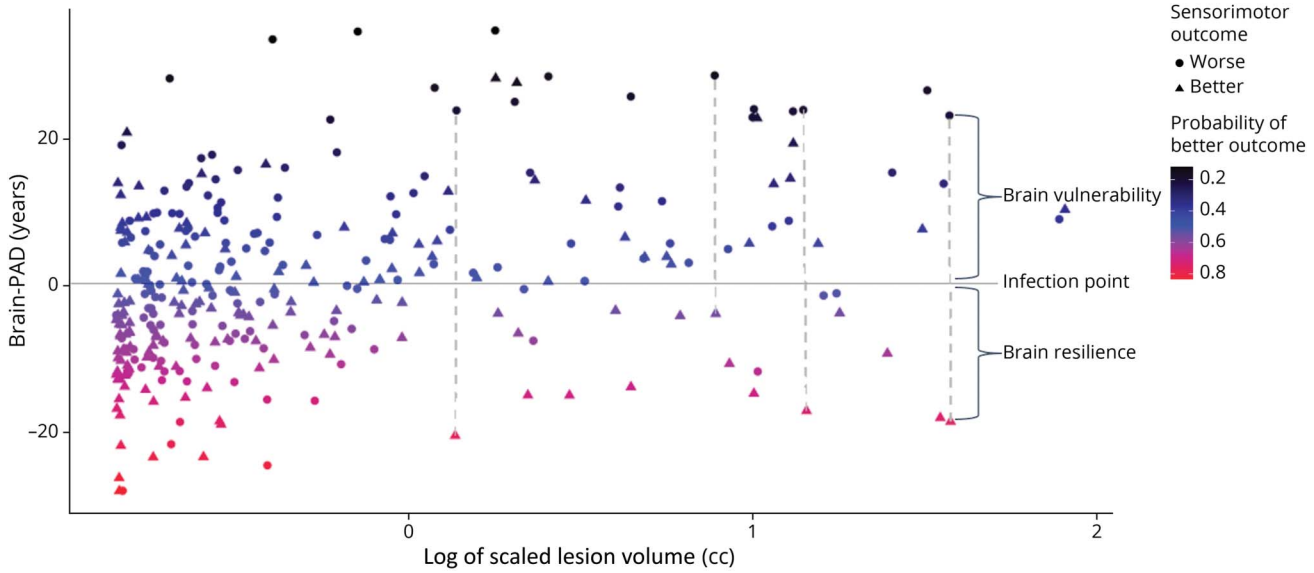
We then tested our hypothesis that the impact of brain-PAD on sensorimotor outcomes is driven by poststroke secondary atrophy, in which case, we expected to see the strongest

Table 3 Brain-PAD Dissociates Good vs Poor Sensorimotor Outcomes

	Sensorimotor outcome (binary) N = 244, R^2 = 0.07				
Predictors	**Odds ratio**	**β**	**SE**	**CI**	***p* Value**
Brain-PAD	**1.04**	**0.04**	**0.01**	**1.01–1.08**	**0.004**
Age	0.99	−0.01	0.01	0.96–1.02	0.476
Sex	1.24	0.22	0.34	0.64–2.42	0.521
ICV	0.86	−0.15	0.17	0.62–1.19	0.377

Abbreviations: brain-PAD = brain-predicted age difference; ICV = intracranial volume.
Summary statistics from the logistic regression showing the impact of brain resilience on outcomes. Good outcome is coded as 0, and poor outcome is coded as 1, such that a higher (worse) brain-PAD is related to a higher likelihood of poor outcome. Sex is coded as a factor (females = 0, males = 1). The sample size (n), conditional R^2, odds ratio, β, SE, 95% CI, and *p* value for all fixed effect covariates are reported. Significant predictors are denoted in bold.

Figure 3 Brain Resilience Dissociates Sensorimotor Outcome



Visualization demonstrating that lower brain-PAD (shown on the y-axis) dissociates those with good (top third) vs poor (bottom third) sensorimotor outcomes (depicted by triangles and circles, respectively), when matched for lesion damage (n = 244). The solid horizontal gray line is the point of inflection where the probability of having a better vs worse outcome is 0.5, with higher probability of better outcome depicted in warmer colors. The logarithm of scaled lesion volume (mL) is shown on the x-axis. Examples of matched pairs with similar lesion volumes, connected by the dotted vertical lines, are shown, with brain resilience shown in association with a lower brain-PAD and brain vulnerability shown in association with a higher brain-PAD. brain-PAD = brain-predicted age difference.

associations in the ipsilesional hemisphere in chronic stroke. Indeed, a larger ipsilesional brain-PAD was negatively associated with worse sensorimotor outcome ($\beta = -0.30$, $p < 0.001$; Table 2). This relationship was maintained when adding total lesion volume and CST-LL into the model ($\beta = -0.17$, $p = 0.008$), suggesting these effects are independent of direct lesion damage (eTable 4, links.lww.com/WNL/C720). There was no detectable association with contralesional brain-PAD ($\beta = -0.05$, $p = 0.436$; eTable 5). There was no association with worse sensorimotor behavior and larger brain-PAD in chronic stroke (n = 558; $\beta = -0.26$, $p = 0.002$; Table 2), but not in early stroke (n = 205; $\beta = -0.13$, $p = 0.386$; eTable 6).

Brain-PAD Mediates the Impact of Lesion Damage on Poststroke Outcomes

In the third step of our mediation analysis, we tested our hypothesis that the relationship between the independent variable (CST-LL) on the dependent variable (poststroke outcomes) is mediated by brain-PAD. We examined this in a subset of the sample with lesion measures (n = 674; see eMethods, eResults, eDiscussion and eTables 7–12, links.lww.com/WNL/C720) and in the ipsilesional hemisphere of patients with chronic stroke only (n = 437), expecting strongest results in ipsilesional chronic stroke in line with our results mentioned earlier. In the whole sample, there was a marginally significant effect of brain-PAD mediating the impact of CST-LL on sensorimotor outcomes (Figure 2), with indirect effects of −0.045 ($p = 0.068$; 95% CI −0.11 to 0.00). The proportion of the effect of CST-LL on sensorimotor outcomes that goes through the mediator (brain-PAD) was 0.04 ($p = 0.068$; 95% CI −0.004 to 0.12). However, as expected, when examining only ipsilesional brain-PAD in chronic stroke (Figure 2), the mediation effect of brain-PAD was significantly stronger. Brain-PAD mediated the impact of CST-LL on chronic sensorimotor outcomes (Figure 2), with indirect effects of −0.11 ($p = 0.007$; 95% CI −0.24 to −0.02). The proportion of the effect of CST-LL on sensorimotor outcomes that goes through the mediator (brain-PAD) was 0.15 ($p = 0.01$; 95% CI 0.03–0.58). In a supplementary analysis, we also show an interaction between CST-LL and brain-PAD, in which brain-PAD has the largest impacts on outcomes when there is little to no CST-LL (n = 748; $\beta = 0.02$, $p = 0.05$; eTable 13).

Structural Brain Resilience Dissociates Good vs Poor Outcomes in People With Matched Focal Lesion Damage

For any given amount of lesion damage, we found that the brain-PAD was highly variable (IQR 16.16 years; range −28.48 to 36.08 years). We therefore tested our fourth hypothesis that greater structural brain resilience, measured as younger brain age despite matched lesion damage, explains why some people have good vs poor outcomes. Propensity score matching was applied to participants with good (n = 249) vs poor (n = 250) sensorimotor outcomes on both lesion volume and CST-LL, resulting in a final matched sample of 244 participants (122 matched samples; 255 unmatched samples were discarded from subsequent analysis). The matching was successful, as evidenced by no difference in either CST-LL or lesion volumes between groups after matching (eTable 14, links.lww.com/WNL/C720).

Using logistic regression, we found that brain-PAD significantly dissociated people with good vs poor outcomes (brain-PAD: odds ratio [OR] 1.04, 95% CI 1.01–1.08, $p = 0.004$; Table 3), such that people with poor outcomes had a higher brain-PAD than people with good outcomes, despite matched CST-LL and lesion volume (brain-PAD: −3.07 ± 10.3 years vs 2.52 ± 11.3 years in better vs worse groups, respectively; Figure 3), even after controlling for age, sex, ICV, and site. Similar results were found when examining only people with chronic stroke using ipsilesional brain-PAD (OR 1.05, 95% CI 1.02–1.08, $p = 0.002$; eTables 15 and 16, links.lww.com/WNL/C720).

Discussion

In this study, we demonstrate that a larger brain age gap is associated with greater stroke damage and longer time after stroke and with worse poststroke functional outcomes. We also show that brain age mediates the relationship between lesion damage and sensorimotor outcomes. This is important because CST integrity has repeatedly been shown to be a robust biomarker of poststroke sensorimotor performance and recovery, and these findings suggest that brain age and brain resilience may modify the impact of focal lesion damage on sensorimotor outcomes, underscoring the key role of neuroimaging markers of biological aging in stroke research.

Stroke has a deleterious effect on the whole brain.[39-42] In this study, we show that after unilateral stroke, older brain age is correlated with smaller cortical and subcortical measurements and larger ventricles, suggesting that brain age captures measures of whole-brain atrophy in stroke. Brain age predicted from the ipsilesional hemisphere was older than brain age predicted from the contralesional hemisphere, suggesting stronger effects in ipsilesional tissue. Larger brain age gap is associated with larger lesion extent, more damage to sensorimotor structures (CST-LL), and longer time after stroke (i.e., more chronic stroke). Altogether, these findings suggest that focal damage may worsen whole brain structural integrity, with stronger effects over time, possibly representative of poststroke secondary atrophy. However, it is unclear what the underlying effect of added brain aging is at different ages in patients with stroke (e.g., a 40-year-old vs a 70-year-old). Future studies should examine the effects of stroke on brain age longitudinally to test the hypothesis that stroke accelerates ipsilesional brain aging, with implications for both outcomes and treatment.

Our study also establishes significant behavioral associations between brain age and functional outcomes in people with stroke. We report associations between worse outcomes and older brain age, both for sensorimotor impairment specifically (FMA-UE) and for general stroke severity (NIHSS). These findings suggest that brain-PAD is a sensitive neuroimaging marker of brain health after stroke across multiple domains. Older brain age, possibly due to poststroke atrophy, may reflect limited capacity for poststroke brain repair and subsequent recovery. Structural loss reflected in older brain age may occur after stroke through multiple pathways, such as through vascular or glymphatic system dysfunction or widespread inflammation.[43,44] Associations between brain age and sensorimotor impairment were strongest in the ipsilesional hemisphere in chronic stroke, suggesting that the relationship is affected by poststroke atrophy. Brain age may be a valuable noninvasive biomarker that represents an amalgamation of neurodegenerative processes, likely accumulated both before and after stroke. Further research with longitudinal data and diverse measures of function are needed to examine whether and how brain age influences poststroke recovery and, conversely, whether and how stroke accelerates brain aging.

In the third step of our mediation analysis, we show that, when examined together with a known focal injury predictor (CST-LL), brain age additionally predicts outcomes, with a causal relationship, such that brain age mediates 15% of the effects of CST-LL on outcomes. This mediation effect is strongest in the ipsilesional hemisphere in chronic stroke, again suggestive of poststroke atrophy. Specifically, we found that larger CST-LL is associated with older brain age, and the resulting older brain age further worsens outcomes beyond the effects of CST-LL alone. Overall, these results suggest that focal damage plus subsequent global damage have an additive effect on sensorimotor outcomes.

Finally, we show that whole-brain structural resilience to lesion damage differentiates people with good vs poor outcomes. Brain age itself was associated with lesion volume, such that larger lesions were associated with larger brain-PAD, but the lesion volume itself did not affect sensorimotor behavior. This suggests that what is important is how the rest of the brain reacts to the lesion (e.g., secondary damage, or conversely, subsequent plasticity)—more so than the amount of damage due to the infarct itself. In line with this, we found that brain age was highly variable across individuals with similar amounts of lesion damage (e.g., Figure 3). We therefore examined whether brain resilience to the lesion, which we defined as lower brain age despite similar amounts of lesion damage, would dissociate people with better vs worse sensorimotor outcomes. Using logistic regression, we found that people with younger brain age tend to be more resilient: their outcomes are better than expected. Contrarily, people with older brain age tend to be less resilient and thus more vulnerable: their outcomes are worse than expected for the same amount of injury. This supports our hypothesis that greater structural brain resilience—as indexed by smaller brain-PAD despite similar amounts of lesion damage—is a significant predictor of better sensorimotor outcomes. Altogether, these results suggest that it is not necessarily the amount of lesion damage during stroke that solely determines sensorimotor outcomes but also the susceptibility of the brain to widespread deterioration after the focal injury.

Although concepts such as brain age and brain resilience are being actively explored in other neurodegenerative fields of

study and in acute stroke,[11,22] there has been limited extension of these concepts particularly to chronic stroke research and in relation to domain-specific rehabilitation outcomes[12] (e.g., FMA). Further research should examine whether brain age can provide a reliable indicator of the brain's readiness for repair by examining whether brain age can predict response to engaging in specific rehabilitation therapies.

Future work would benefit from large-scale longitudinal studies to measure the trajectory of brain aging during the weeks after a stroke to ascertain whether stroke accelerates brain aging. This is critical because recent work suggests that cross-sectional brain age may reflect either early-life differences or volume loss due to isolated incidents, such as stroke.[45] Furthermore, as previously noted,[24,25] although our large heterogeneous dataset provides statistical power and diverse data to test hypotheses, there are limited covariates that are present across the entire dataset. Additional factors known to influence brain age—such as genetics, neurodegenerative copathology such as microvascular damage, lifestyle factors, and comorbidities—should be examined in future studies. Additional harmonization of prospectively collected data across the acute and chronic stroke timeline, as recommended by the Stroke Recovery and Rehabilitation Roundtable,[46,47] would also allow for larger samples to explore questions more broadly and with greater power. In addition, while we show that lesion volume is related to older brain age, it is possible that larger lesions could bias brain age estimation. However, previous studies using similar FreeSurfer-based methods have demonstrated reliable brain age estimates in stroke,[20,21] and we used several additional quality control steps to prevent skewed brain age estimations (see eMethods, links.lww.com/WNL/C720). Finally, because there is now active research examining treatments to prevent or slow brain aging (e.g., from aging and Alzheimer disease research),[48,49] these interventions should be explored to assess whether they could improve functional outcomes after stroke.

Study Funding

A.G. Brodtmann is supported by Australian National Health and Medical Research Council (NHMRC) GNT1020526, GNT1045617(AB), GNT1094974; Brain Foundation; Wicking Trust; Collie Trust; Sidney and Fiona Myer Family Foundation; and Heart Foundation Future Leader Fellowship 100784. C.M. Buetefisch is supported by NIH R01NS090677. W.D. Byblow is supported by the Health Research Council of New Zealand. J.M. Cassidy is supported by NIH R00 HD091375. A.B. Conforto is supported by NIH R01 NS076348; IIEP-2250-14. S.C. Cramer is supported by U01 NS120910, R01 HD095457, and R01 NR015591. A.N. Dula is supported by Lone Star Stroke Research Consortium. N. Egorova-Brumley is supported by Melbourne Research Fellowship. F. Geranmayeh is supported by Wellcome Trust (093957). L.K.M. Han is supported by a Rubicon fellowship provided by The Dutch Research Council (NWO). T. Hahn is supported by the German Research Foundation (DFG grants HA7070/2-2, HA7070/3, HA7070/4 to T.H.). B. Hordacre is supported by National Health and Medical Research Council (NHMRC) fellowship (GNT1125054). S.A. Kautz is supported by NIH P20 GM109040, 1IK6RX003075. M.S. Khlif is supported by National Health and Medical Research Council (NHMRC) grant (APP1020526). S.-L. Liew is supported by NIH R01 NS115845. B.J. MacIntosh is supported by Canadian Partnership for Stroke Recovery, Sandra E Black Centre for Brain Resilience & Recovery. M. Mataro is supported by ICREA Academia program. F. Piras is supported by Italian Ministry of Health, Ricerca Corrente, RC 21, 22. K.P. Revill is supported by NIH R01NS090677. H.M. Schambra is supported by National Institute of Neurological Disorders and Stroke (NINDS) R01 NS110696. L. Schmaal is supported by National Institute of Mental Health of the NIH (R01MH117601) and by a National Health and Medical Research Council (NHMRC) Career Development Fellowship (1140764). N. Schweighofer is supported by NIH R56 NS100528. N.J. Seo is supported by NIH/NICHD 1R01HD094731-01A1, VA RR&D I01 RX003066, U54-GM104941, and P20GM109040. S.R. Soekadar is supported by the European Research Council (ERC) grant 759370. G. Spalletta is supported by Italian Ministry of Health, RC 18-19-20-21-22/A. C.M. Stinear is supported by Health Research Council of New Zealand. M. Taga is supported by NIH R01 NS110696. G. Thielman is supported by Temple University subaward of NIH R24–NHLBI (Dr. Mickey Selzer) Center for Experimental Neurorehabilitation Training. P.M. Thompson is supported by NIH U54 EB020403. L.T. Westlye is supported by European Research Council under the European Union's Horizon 2020 research and Innovation program (ERC StG, grant 802998), the Research Council of Norway (298646, 300767), and the South-Eastern Norway Regional Health Authority (2019101). C.J. Winstein is supported by grants HD065438 and NS100528. G.F. Wittenberg is supported by VA RR&D program, NSF, and serves on the Medical Advisory Board of Myomo, Inc., a manufacturer of rehabilitation-related equipment. S.L. Wolf is supported by VA SPiRE 1I21RX003581-01 grant 13039842; REGE19000049 NIH-NIDILRR RERC Program; NIH NICHD 1R01HD095975-01A1; NINDS U01 NS102353; NINDS U01 NINDS NS166655; and NINDS1U10NS086607.

Disclosure

S.-L. Liew and N. Schweighofer report no disclosures relevant to the manuscript. J.H. Cole is a scientific advisor to and shareholder in Brain Key, Claritas HealthTech. A. Zavaliangos-Petropulu, B.P. Lo, L.K.M. Han, T. Hahn, L. Schmaal, M.R. Donnelly, J.N. Jeong, Z. Wang, A. Abdullah, J.H. Kim, A. Hutton, G. Barisano, M. R. Borich, and L.A. Boyd report no disclosures relevant to the manuscript. A.G. Brodtmann has received consultancy fees from Biogen Australia and Roche Australia for Scientific Advisory Board contributions. C. Buetefisch, W.D. Byblow, J.M. Cassidy, C.C. Charalambous, V. Ciullo, A.B. Conforto, R. Dacosta-Aguayo, J.A. DiCarlo, M. Domin, A.N. Dula, N. Egorova-Brumley, W. Feng, F. Geranmayeh, C.M. Gregory, C.A. Hanlon, K.S. Hayward, and J.A. Holguin report no disclosures relevant to the manuscript. B. Hordacre holds a paid consultancy role for Recovery VR and has a clinical partnership with Fourier Intelligence. N. Jahanshad, S.A. Kautz, M.S. Khlif, H. Kim, A. Kuceyeski, D.J. Lin, J. Liu, M. Lotze, B.J. MacIntosh, J.L. Margetis, M. Mataro, F.B. Mohamed, E.R. Olafson, G. Park, F.

Piras, K.P. Revill, P. Roberts, A.D. Robertson, N. Sanossian, H.M. Schambra, N.J. Seo, S.R. Soekadar, G. Spalletta, C.M. Stinear, M. Taga, W.K. Tang, G.T. Thielman, D. Vecchio, N.S. Ward, L.T. Westlye, and C.J. Winstein report no disclosures relevant to the manuscript. G.F.W. is on the Medical Advisory Board, Myomo, Inc. S.L. Wolf is a consultant for Microtransponder, Inc., Enspire, Inc., and SAEBO. K.A. Wong and C. Yu report no disclosures relevant to the manuscript. S.C. Cramer serves as a consultant for Abbvie, Constant Therapeutics, BrainQ, Myomo, MicroTransponder, Neurolutions, Panaxium, NeuExcell, Elevian, and TRCare. P.M. Thompson received research support from Biogen, Inc., for research unrelated to this manuscript. Go to Neurology.org/N for full disclosures.

Publication History

Previously published at bioRxiv doi: 10.1101/2022.04.27.489791 Received by *Neurology* October 16, 2022. Accepted in final form February 8, 2023. Submitted and externally peer reviewed. The handling editor was Editor-in-Chief José Merino, MD, MPhil, FAAN.

Appendix 1 Coinvestigators

Coinvestigators are listed at links.lww.com/WNL/C781.

References

1. Ito KL, Kim B, Liu J, et al. Corticospinal tract lesion load originating from both ventral premotor and primary motor cortices are associated with post-stroke motor severity. *Neurorehabil Neural Repair*. 2021;36(3):179-182.
2. Feng W, Wang J, Chhatbar PY, et al. Corticospinal tract lesion load: an imaging biomarker for stroke motor outcomes. *Ann Neurol*. 2015;78(6):860-870. doi:10.1002/ana.24510
3. Riley JD, Le V, Der-Yeghiaian L, et al. Anatomy of stroke injury predicts gains from therapy. *Stroke*. 2011;42(2):421-426.
4. Stinear CM, Byblow WD, Ackerley SJ, Smith MC, Borges VM, Barber PA. PREP2: a biomarker-based algorithm for predicting upper limb function after stroke. *Ann Clin Transl Neurol*. 2017;4(11):811-820.
5. Rinne P, Hassan M, Fernandes C, et al. Motor dexterity and strength depend upon integrity of the attention-control system. *Proc Natl Acad Sci USA*. 2018;115(3):E536-E545.
6. Foulon C, Cerliani L, Kinkingnehun S, et al. Advanced lesion symptom mapping analyses and implementation as BCBtoolkit. *GigaScience*. 2018;7(3):giy004.
7. Thiebaut de Schotten M, Foulon C. The rise of a new associationist school for lesion-symptom mapping. *Brain*. 2017;141(1):2-4.
8. Frost S, Barbay S, Friel K, Plautz E, Nudo R. Reorganization of remote cortical regions after ischemic brain injury: a potential substrate for stroke recovery. *J Neurophysiol*. 2003;89(6):3205-3214.
9. van Meer MP, Otte WM, van der Marel K, et al. Extent of bilateral neuronal network reorganization and functional recovery in relation to stroke severity. *J Neurosci*. 2012;32(13):4495-4507.
10. Appleton JP, Woodhouse LJ, Adami A, et al. Imaging markers of small vessel disease and brain frailty, and outcomes in acute stroke. *Neurology*. 2020;94(5):e439-e452.
11. Bu N, Khlif MS, Lemmens R, et al. Imaging markers of brain frailty and outcome in patients with acute ischemic stroke. *Stroke*. 2021;52(3):1004-1011.
12. Cramer SC, Koroshetz WJ, Finklestein SP. The case for modality-specific outcome measures in clinical trials of stroke recovery-promoting agents. *Stroke*. 2007;38(4):1393-1395.
13. Cole JH, Franke K. Predicting age using neuroimaging: innovative brain ageing biomarkers. *Trends Neurosci*. 2017;40(12):681-690.
14. Cole JH, Ritchie SJ, Bastin ME, et al. Brain age predicts mortality. *Mol Psychiatry*. 2018;23(5):1385-1392.
15. Franke K, Gaser C. Ten years of BrainAGE as a neuroimaging biomarker of brain aging: what insights have we gained? *Front Neurol*. 2019;10:789.
16. Han LKM, Dinga R, Hahn T, et al. Brain aging in major depressive disorder: results from the ENIGMA major depressive disorder working group. *Mol Psychiatry*. 2021;26(9):5124-5139. doi:10.1038/s41380-020-0754-0
17. Cole JH, Leech R, Sharp DJ; Alzheimer's Disease Neuroimaging Initiative. Prediction of brain age suggests accelerated atrophy after traumatic brain injury. *Ann Neurol*. 2015;77(4):571-581.
18. Cole JH, Raffel J, Friede T, et al. Longitudinal assessment of multiple sclerosis with the brain-age paradigm. *Ann Neurol*. 2020;88(1):93-105.
19. Gaser C, Franke K, Klöppel S, Koutsouleris N, Sauer H; Alzheimer's Disease Neuroimaging Initiative. BrainAGE in mild cognitive impaired patients: predicting the conversion to Alzheimer's disease. *PLoS One*. 2013;8(6):e67346.
20. Egorova N, Liem F, Hachinski V, Brodtmann A. Predicted brain age after stroke. *Front Aging Neurosci*. 2019;11:348.
21. Richard G, Kolskår K, Ulrichsen KM, et al. Brain age prediction in stroke patients: highly reliable but limited sensitivity to cognitive performance and response to cognitive training. *Neuroimage: Clin*. 2020;25:102159.
22. De Godoy LL, Alves CAPF, Saavedra JSM, et al. Understanding brain resilience in superagers: a systematic review. *Neuroradiology*. 2021;63(5):663-683.
23. Park C-h, Kim BR, Park HK, et al. Predicting superagers by machine learning classification based on the functional brain connectome using resting-state functional magnetic resonance imaging. *Cereb Cortex*. 2021;32(19):4183-4190.
24. Liew S-L, Zavaliangos-Petropulu A, Schweighofer N, et al. Smaller spared subcortical nuclei are associated with worse post-stroke sensorimotor outcomes in 28 cohorts worldwide. *Brain Commun*. 2021;3(4):fcab254. doi:10.1101/2020.11.04.366856
25. Zavaliangos-Petropulu A, Lo B, Donnelly M, et al. Chronic stroke sensorimotor impairment is related to smaller hippocampal volumes: an ENIGMA analysis. *J Am Heart Assoc*. 2022;11(10):e025109.
26. Zhang J, Zhang Y, Xing S, Liang Z, Zeng J. Secondary neurodegeneration in remote regions after focal cerebral infarction: a new target for stroke management? *Stroke*. 2012;43(6):1700-1705.
27. Liew SL, Zavaliangos-Petropulu A, Jahanshad N, et al. The ENIGMA Stroke Recovery Working Group: big data neuroimaging to study brain-behavior relationships after stroke. *Hum Brain Mapp*. 2022;43(1):129-148. doi:10.1002/hbm.25015
28. Liew SL, Anglin JM, Banks NW, et al. A large, open source dataset of stroke anatomical brain images and manual lesion segmentations. *Sci Data*. 2018;5(1):180011.
29. Liew S-L, Lo B, Donnelly MR, et al. A large, curated, open-source stroke neuroimaging dataset to improve lesion segmentation algorithms. *medRxiv*. 2021:2021.12.09.21267554. doi:10.1101/2021.12.09.21267554
30. Ito KL, Kumar A, Zavaliangos-Petropulu A, Cramer SC, Liew S-L. Pipeline for analyzing lesions after stroke (PALS). *Front Neuroinformatics*. 2018;12:63.
31. Archer DB, Vaillancourt DE, Coombes SA. A template and probabilistic atlas of the human sensorimotor tracts using diffusion MRI. *Cereb Cortex*. 2018;28(5):1685-1699.
32. Brott T, Adams HP Jr, Olinger CP, et al. Measurements of acute cerebral infarction: a clinical examination scale. *Stroke*. 1989;20(7):864-870.
33. Rungtusanatham M, Miller J, Boyer KK. Theorizing, testing, and concluding for mediation in SCM research: tutorial and procedural recommendations. *J Oper Manag*. 2014;32(3):99-113.
34. Memon MA, Cheah JH, Ramayah T, Ting H, Chuah F. Mediation analysis issues and recommendations. *J Appl Struct Equat Model*. 2018;2(1):i-ix.
35. Woytowicz EJ, Rietschel JC, Goodman RN, et al. Determining levels of upper extremity movement impairment by applying a cluster analysis to the Fugl-Meyer assessment of the upper extremity in chronic stroke. *Arch Phys Med Rehabil*. 2017;98(3):456-462.
36. Ho DE, King G, Imai K, Stuart EA. MatchIt: nonparametric preprocessing for parametric causal inference. *J Stat Softw*. 2011;42(8).
37. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing; 2013.
38. Le TT, Kuplicki RT, McKinney BA, Yeh HW, Thompson WK, Paulus MP; Tulsa 1000 Investigators. A nonlinear simulation framework supports adjusting for age when analyzing BrainAGE. *Front Aging Neurosci*. 2018;10:317.
39. Carmichael ST, Tatsukawa K, Katsman D, Tsuyuguchi N, Kornblum HI. Evolution of diaschisis in a focal stroke model. *Stroke*. 2004;35(3):758-763.
40. Carrera E, Tononi G. Diaschisis: past, present, future. *Brain*. 2014;137(9):2408-2422.
41. Cheng B, Dietzmann P, Schulz R, et al. Cortical atrophy and transcallosal diaschisis following isolated subcortical stroke. *J Cereb Blood Flow Metab*. 2020;40(3):611-621.
42. Seitz RJ, Azari NP, Knorr U, Binkofski F, Herzog H, Freund H-J. The role of diaschisis in stroke recovery. *Stroke*. 1999;30(9):1844-1850.
43. Ward NS. Restoring brain function after stroke—bridging the gap between animals and humans. *Nat Rev Neurol*. 2017;13(4):244-255.
44. Murphy TH, Corbett D. Plasticity during stroke recovery: from synapse to behaviour. *Nat Rev Neurosci*. 2009;10(12):861-872.
45. Vidal-Pineiro D, Wang Y, Krogsrud SK, et al. Individual variations in 'brain age'relate to early-life factors more than to longitudinal brain change. *Elife*. 2021;10:e69995.
46. Bernhardt J, Hayward KS, Kwakkel G, et al. Agreed definitions and a shared vision for new standards in stroke recovery research: the stroke recovery and rehabilitation roundtable taskforce. *Int J Stroke*. 2017;12(5):444-450.
47. Kwakkel G, Lannin NA, Borschmann K, et al. Standardized measurement of sensorimotor recovery in stroke trials: consensus-based core recommendations from the stroke recovery and rehabilitation roundtable. *Neurorehabil Neural Repair*. 2017;31(9):784-792.
48. Lerner AJ, Pieper AA. *Neurotherapeutics of the Aging Brain: Complexity Meets Complexity*. Springer; 2019:539-542.
49. McFall GP, McDermott KL, Dixon RA. Modifiable risk factors discriminate memory trajectories in non-demented aging: precision factors and targets for promoting healthier brain aging and preventing dementia. *J Alzheimers Dis*. 2019;70(s1):S101-S118.

Association of Brain Age, Lesion Volume, and Functional Outcome in Patients With Stroke

Sook-Lei Liew, Nicolas Schweighofer, James H. Cole, et al.

Neurology 2023;100;e2103-e2113 Published Online before print April 4, 2023
DOI 10.1212/WNL.0000000000207219