**Clinical Trials in Vascular Cognitive Impairment following SPRINT-MIND.**

**An International Perspective**

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**Summary**

A large interventional trial, SPRINT-MIND, found reduced risk of cognitive impairment in older adults with intensive, relative to standard, blood pressure-lowering targets (systolic BP<120 vs. <140 mmHg). In this Perspective we discuss key questions and make recommendations for clinical practice and for clinical trials, following SPRINT-MIND.

Future trials should embody cognitive endpoints appropriate to the participant group, ideally with adaptive designs that assure robust answers for cognitive and cardiovascular endpoints. Reliable data from diverse populations, including the oldest-old (age>80), will maximise external validity and global implementation of trial findings. New biomarkers will improve phenotyping, to stratify patients to optimal treatments. Currently no antihypertensive drug-class stands out for dementia risk reduction. Multi-domain interventions, incorporating lifestyle change (exercise, diet) alongside medications, may maximise global impact. Given the low cost and wide availability of antihypertensive drugs, intensive BP reduction may be a cost-effective means to reduce dementia risk in diverse, aging populations worldwide.

**Keywords**. Hypertension; blood pressure; dementia; cognitive impairment; clinical trials; aging; vascular disease; prevention

**Introduction**

Vascular disease is now recognised as a major contributing factor in dementia, usually as a comorbid condition with Alzheimer’s disease (AD)1-3. Vascular risk factors contribute to cognitive impairment4 and are recognized risk factors for dementia5. Acknowledging the major contributions of vascular disease to cognitive impairment has led to the concept of Vascular Contributions to Cognitive Impairment and Dementia (VCID)6. The importance of VCID and the heterogeneity of dementia pathology3 has implications for prevention and precision medicine. This is especially important in diverse populations where ethnic differences affect the prevalence of vascular comorbidities7, 8.

Recently observed declines in the age-specific incidence of dementia in North America and Europe have shown that dementia risk is modifiable, likely due to better cardiovascular risk management9. Whilst these trends temper the increasing burden of dementia, prevalence is still expected to rise substantially over the next decades9, 10, particularly in low- and middle-income countries (LMIC). Targeted treatments are therefore important, but few licenced drug treatments are available. For twenty years these were limited to three acetylcholinesterase inhibitors and a non-selective NMDA receptor antagonist, all with modest clinical effects. Amyloid-depleting antibodies aducanumab and lecanemab were recently approved by the U.S. Food and Drug Administration (FDA) for Alzheimer-type dementia.11, 12. Given the sparse treatment options, therapeutic strategies for prevention of dementia are much needed. Treatment of vascular risk factors may offer novel therapeutic targets for dementia prevention and treatment13, 14.

The Systolic Blood Pressure Intervention Trial sub-study termed Memory and Cognition in Decreased Hypertension (SPRINT-MIND) was a large multi-centre study comparing intensive blood pressure lowering (target: SBP <120 mmHg) with a standard BP target (SBP<140 mmHg). There was significant 20-30% reduction in risk for major cardiovascular events with intensive BP lowering (the primary outcome of the parent study, SPRINT)15, 16. This led to early termination of the trial by the sponsor at 3.3 years, rather than the planned 6 years. The intensive intervention showed a null effect on the SPRINT-MIND primary endpoint of dementia diagnosis, possible due to the reduced duration of the study. Nevertheless, intensive BP-lowering significantly reduced mild cognitive impairment (MCI) and a combined adjudicated cognitive endpoint of MCI or probable dementia15.

These positive findings of a cognitive benefit in a large interventional trial are the basis for our emphasis on SPRINT-MIND in this perspective. Evidence for cognitive treatment benefits in the dementia field are few. That said, there have been several previous large trials in the area of BP-lowering for cognitive benefit, previously reviewed17. Individually these trails were not decisive in demonstrating significant benefit in terms of reducing dementia risk17. A recent meta-analysis of individual participant data from five large double-blinded studies, ADVANCE, PROGRESS, SHEP, SYST-EUR and HYVET (data from N=28,000 participants in total) detected a significant reduction in dementia risk with late life BP lowering18.

A major strength of SPRINT was that it was not designed to test any particular drug class, but rather the hypothesis that BP lowering impacts end-organ dysfunction. The results were consistent with recent large meta-analyses of BP-lowering studies, concluding that the cognitive benefits of BP control are not strongly dependent on a specific class of medication19, 20. The results also demonstrated that generic, and therefore low-cost, formulations of standard BP-lowering drugs are adequate to achieve the cognitive preservation reported in SPRINT-MIND. Population modelling predicts that substantial global cardiovascular disease (CVD) prevention could be achieved with generic medications at an average cost of approximately one US dollar per year21. Furthermore, a recent review suggests that the majority of published studies on cost-effectiveness of hypertension interventions (both pharmaceutical only and combination programs) in LMIC demonstrate cost-effectiveness when evaluated based on cost per averted disability-adjusted life-year (DALY)22. Thus, intensive BP reduction may be a cost-effective means to reduce dementia risk in older people from diverse economic backgrounds worldwide.

There are caveats to this encouraging concept. Intensive BP lowering requires careful monitoring by physicians and other healthcare professionals. Also, despite clinical trial evidence to the contrary23 many geriatricians, internists and primary care physicians are reluctant to lower BP intensively in older persons, fearing to compromise cerebral blood flow (CBF). In addition, because most older patients – particularly vascular patients – have a high prevalence of multiple comorbidities (chronic renal disease, diabetes mellitus, pulmonary disease, rheumatologic and neurological conditions)24 and the attendant co-medications, there is reluctance to support intensive BP control requiring additional medication. Thus, managing prevention of VCID in older people will require a multifactorial approach. Finally, we cannot assume that a US-based treatment regimen (as in SPRINT-MIND) will translate straightforwardly to diverse populations in other global healthcare settings.

In this Perspective we review the implications of SPRINT-MIND for current clinical practice, and for future trials, by discussing 10 outstanding questions. Can SPRINT-MIND findings translate into frontline clinical practice? Do they apply in LMIC? Should inclusion criteria be broad or narrow? Who needs to be treated and when? Is cerebral hypoperfusion or orthostatic hypotension a concern? Are particular drug classes most beneficial? Would a combined approach including lifestyle interventions be preferable? Can genetics and biomarkers improve risk stratification? Should we include the oldest-old in future trials? Is it ethical to include a control group without intensive BP lowering? We offer suggestions for future trial design and practical implementation.

**SPRINT-MIND. Design and outcomes.**

*Design*. The parent trial SPRINT randomised participants to a cardiovascular drug regimen of either intensive or standard BP-lowering, standard being the American Heart Association-guideline goal at the time of trial initiation (SBP<140 mmHg). The primary hypothesis was that CVD event rates would be lower in the intensive arm. The design is summarised in Table 1.

**Table 1. Overview of the SPRINT trial design \*\*\*\*\*\*\* Near here**

*Interventions*. SPRINT was an open-label trial. Use of once-daily antihypertensive agents was encouraged unless alternative frequency was indicated/necessary. One or more medications from the classes listed in Table 1 were provided by the study for use in managing participants in both randomization groups. Preferred regimens included a thiazide diuretic (drug of choice: chlorthalidone), plus CCB (drug of choice: amlodipine), plus ACE inhibitor/ARB (Table 1). The order in which agents were selected was left to the investigator. It was expected that many patients would need at least 3 antihypertensive drugs to achieve SBP <120 mmHg. Most (90%) of the medications used in SPRINT were generic drugs.

*Outcomes*. A total of 9361 older Americans were enrolled, including 35.6% women, 30% African American and 10.5% Hispanic. 1167 (12.5%) were aged 80 or more at entry16. Early termination of the trial (at 3.3 y) resulted in limited follow-up time to observe the development of dementia. Follow-up for cognitive and kidney outcomes continues during the post-intervention phase.

In terms of cognitive outcomes, intensive treatment did not lead to decreased risk of probable dementia over a median follow-up of 5.1 years, though it reduced the occurrence of MCI and a composite measure combining MCI or probable dementia (Table 2)15. In a non-random subgroup of participants that received comprehensive neuropsychological testing at each cognitive assessment, intensive treatment showed no difference on a composite measure of memory function, but slighter larger decreases on a composite measure of processing speed (driven by small differences on the Trail Making Test-Part B)25. Somewhat contrasting results were observed in an MRI sub-study. Intensive treatment was associated with a smaller increase in the volume of white matter lesions (WML), an MRI marker for cerebral small vessel disease (SVD)26 and with increased cerebral blood flow27-29. By contrast, intensive treatment was associated with larger decreases in total brain volume and hippocampal volume27-29. Smaller increases in WML volume and larger decreases in total brain volume were similarly observed with intensive treatment in another large trial (ACCORD) 30.

**Table 2. What SPRINT-MIND Showed. Cognitive and MRI Outcomes \*\*\*\*\*\* Near here**

*What are the lessons learned from SPRINT MIND? What should be done differently in future trials?*

Adaptive design. Early termination of SPRINT due to the success in reducing major cardiovascular outcomes of death, myocardial infarction and stroke, reduced the power to detect the impact of treatment on cognitive outcomes. This is compounded by gradual return of BP to pre-enrolment levels following trial completion31. With hindsight, the design of SPRINT should have included an alternative design trigger, that facilitated continued assessment of cognitive outcomes beyond the finding of a beneficial effect on CVD. Effects on cognitive function require longer-term follow-up than CVD endpoints. For this reason, it will be advantageous to include adaptive trial designs in future studies assessing cognitive impact, especially if there is CVD assessment in the trial. For example, study participants may be enrolled in an extended open-label treatment protocol to assess the impact of both short and longer-term treatment on cognitive outcomes.

Additional endpoints. Other endpoints more sensitive to the impact of CVD on brain structure and function could be included, to support the biological plausibility of treatment efficacy. Such surrogate markers could include the burden of SVD and white matter microstructure. Additionally, assessment of potential intermediates and effect-modifying characteristics (pulse wave velocity, BP variability) may help to understand which BP lowering interventions are most efficacious, and in which patients.

Several recent prospective cohort studies (Diverse-VCID; MESA-MIND)32 were designed to examine pathways by which vascular risk factors contribute to cognitive decline in diverse groups of at-risk individuals. These studies will likely identify new biomarkers and intervention targets. MarkVCID33, 34 and the HARNESS Initiative35 are consortia currently examining and harmonizing various blood-based and imaging outcome biomarkers to identify the best measures for clinical trials related to VCID. Advanced diffusion-based MRI techniques are increasingly being employed to image white matter microstructural injury35, 36.

Greater Diversity. SPRINT-MIND was a US-based study. Greater geographic diversity in trials will be advantageous, not only to understand intervention impacts in diverse populations7, but also because countries with high prevalence of hypertension stand to benefit most at the population level. This is critical in LMIC given their increasing dementia incidence. The PROGRESS study included some diversity37, but did not specifically target diverse individuals at highest risk for hypertension, such as African Americans. Risk stratification, therefore, should be considered along with diverse inclusion in designing future trials.

*Summary*. The lessons learned from SPRINT-MIND include: adaptive trial protocols; integration of cognitive outcomes in cardiovascular treatment trials; proposed lengthening of such trials for cognitive outcomes, possibly through open-label extension, when the primary cardiovascular outcomes are attained; increasing participant diversity, and risk stratification in study design. We welcome development of better vascular biomarkers for assessment of brain injury and for use as secondary measures in treatment trials.

*Is there a need for earlier interventions? And longer trials?*

Results from SPRINT-MIND emphasise the need for timely intervention, in line with the stronger link of mid-life CVD risk factors (especially BP) with dementia incidence, compared to late-life risk factors38. Although in SPRINT-MIND only 3.3 years of treatment were needed to show cognitive benefit, it seems likely that benefits will increase with more prolonged treatment (5 years or more). Reductions in BP from mid-life onwards, either through individualised or public health interventions, may therefore help to maintain cognitive health into old age.

Because dementia reflects end-organ damage to the brain, trials should focus on the inclusion of participants who are at risk and monitor events over longer periods of time. This has financial implications requiring commitment from governments and funders, particularly if trials are to be conducted in younger populations, where dementia incidence is low and cognitive testing can be hampered by ceiling effects. Sensitive and well-validated surrogate outcome measures may aid in detecting treatment effects in individuals, prior to the onset of cognitive deficits. Detection of early cognitive impairment is a priority, with a focus on its prevention in the phase of subjective complaints (or even before). This requires increased public awareness about the benefits of treatment before the onset of cognitive impairment38, which in turn has implications for developing methods for managing inclusion of trial populations. Recognition of VCID should be highlighted across different settings, including primary care and public health campaigns within the community.

*Summary*. The optimal approach to dementia prevention through BP lowering starts in mid-life and will require individual as well as population interventions. Feasibility of individual participant trials will depend on prolonged duration of observation and treatment, and employment of more sensitive (possibly subclinical) outcome measures.

*Is orthostatic hypotension a concern?*

Orthostatic hypotension (OH) refers to the acute fall in BP that results from standing up suddenly, from a sitting or lying position. OH is often due to slowing of the autonomic reflexes that maintain adequate perfusion pressure, and is frequently seen in older persons. A salient concern with OH is the risk of insufficient brain perfusion and possible loss of consciousness. There is a theoretical concern that intensive BP lowering may compromise CBF, and many medical personnel are apprehensive about intensive treatment at older ages. Observational evidence has suggested adverse outcomes of a lower BP, including cognitive decline and mortality39. In patients with impaired CBF autoregulation, intensive BP lowering could indeed be a cause for concern, however, research in older people shows that in fact autoregulation remains largely intact with aging40, 41, even in persons with MCI and dementia42. Measuring CBF before and after BP lowering in people with hypertension, including older adults, as a rule revealed no reductions in cerebral perfusion41. This was confirmed in a recent systematic review, which included MCI and dementia23. In SPRINT-MIND, intensive treatment was associated with a small but significant increase (4%) in whole-brain CBF (Table 2)27. Smaller studies confirm that there is no concern for a reduction in CBF with intensive BP lowering23, 43.

In SPRINT, incidence of OH was not more common in the intensive BP-lowering group, nor was baseline OH associated with incidence of adverse events. There was more self-reported or clinician-reported syncope in the intensive group relative to the control group (3.5% vs 2.4%) 44 but with the caveat of possible bias due to “open label” treatment allocation. There was no increase in electrolyte abnormalities, acute renal failure or injurious falls in the intensive group. A careful examination of OH in SPRINT and meta-analysis of several RCTs of antihypertensive therapy concluded that “symptomless OH during hypertension treatment should not be viewed as a reason to down-titrate therapy even in the setting of a lower BP goal”45, 46. Limitations of these studies were that OH was measured only using the transition from sit-to-stand, which is less sensitive than supine-to-stand, and only at one minute. Future studies should include more detailed measures of OH at initiation and discontinuation of antihypertensive therapy.

While SPRINT did not include persons with prevalent dementia, it is important to recall that concerns of autonomic dysfunction in dementia are mainly based on Lewy Body dementia and Parkinson’s disease dementia, with limited evidence of autonomic dysfunction in AD and vascular dementia. In the NILVAD trial testing the CCB nilvadipine in AD patients47, and in several smaller studies, there was also no evidence of increased risk of OH in patients with dementia, also with prolonged standing (up to 5 minutes)42.

*Summary*. For older people without dementia, OH appears not to be a major concern in BP lowering, and the prevalence of autonomic dysfunction is low (in view of physiological data from patients with AD, as well as SPRINT-MIND). High BP is itself an important cause of OH, and persons exhibiting OH may benefit from antihypertensive treatment. Overall, current evidence suggests that BP lowering does not lead to CBF reduction in older patients, with or without cognitive impairment or dementia.

*How to translate the SPRINT-MIND findings into a frontline clinical setting? Who needs to be treated, when do they need to be treated, and to what target?*

From a clinical perspective, early recognition of vascular risk factors is key, as is the need to identify and prioritize treatment of risk factors with the largest health effect. For instance, the decrease in BP from baseline (the so-called “delta”) may be more important for cognition than an absolute BP target (such as SBP<120mmHg). Rather than one BP fits all, individuals with diverse risk factors, co-morbidities, and biological characteristics may require different BP thresholds. After termination of SPRINT-MIND, SBP in the intensively treated group increased back towards previous guideline levels within 4-5 years31. Not surprisingly, maintaining lower SBP, closer to 120 mmHg, requires ongoing monitoring and management.

Despite the demonstrated benefits of BP lowering, mechanisms underpinning this remain to be elucidated. Understanding the molecular pathways modified will provide an opportunity to target these pathways, with a larger effect size. There remains an outstanding question of whether the benefits of BP lowering on cognition are mediated through neurodegenerative molecular dysfunctions, such as loss of neuro-glial proteostasis, or through a blood vessel delimited process. Implementation of molecular biomarkers in future trials will shed light on these important unknowns, with great relevance to preventative therapeutics for dementia.

Currently the only vascular and neurodegenerative risk stratification performed in clinical practice is through structural brain imaging, vital signs, and some basic laboratory tests. While more sensitive imaging and molecular biomarkers will improve clinical risk stratification, the feasibility of implementing these within large healthcare systems is a considerable challenge. Routine assessment of cerebral autoregulation, blood-brain barrier function and neurovascular coupling, all important contributions from vascular dysfunction to cognitive impairment, are not currently feasible at scale in clinical practice. While such measurements are performed in research groups, thresholds and clinical interpretation at n-of-1 levels, needed for implementation in clinical practice, remain to be determined.

Implementing sensitive and specific vascular biomarkers that can be quantified non-invasively (for example, in blood) and are interpretable on an n-of-1 level will change clinical practice and prove instrumental for identifying persons at high risk, and for guiding personalized, impactful interventions. Akin to their use in cancer and heart disease, biomarkers (imaging and molecular) in VCID can help to: 1) stratify persons at increased risk of VCID who are most suited for interventions; 2) guide the selection and tailoring of the intervention to the individual (“n=1 medicine”); 3) monitor the response to treatment; 4) minimize side-effects. The MarkVCID consortium is developing biomarkers of VCID for future clinical trials. MarkVCID initially evaluated 11 novel fluid34 and neuroimaging-based33 biomarkers of SVD, several of which progressed to the second round of clinical validations. Three novel fluid biomarkers for VCID were identified: plasma VEGF, placental growth factor (PIGF) and FGF-234, 48. In addition, CSF concentrations of PlGF, and two endothelial inflammation markers (C3b and Bb measured from endothelial-derived extracellular vesicles) were deemed to be too early in development to be validated for clinical trials34, 48. These promising biomarkers continue to be investigated, with potential to give invaluable specificity for vascular disease. The initial neuroimaging-based candidate biomarkers include WML volume, WML growth/regression, peak width of skeletonized mean diffusivity, arteriolosclerosis, MRI free water, cerebrovascular reactivity, and optical coherence tomography angiography (OCTA) for retinal capillaries33. From this list WML volume and OCTA were eliminated from further validations in MarkVCID. Subcortical CBF49 and cerebral vasoreactivity50 have been recently used as outcome measures in clinical trials. Overall, vascular biomarkers have the potential to facilitate the early identification of SVD pathology and offer better monitoring of disease progression or intervention efficacy.

*Summary*. Effective BP treatment for cognitive health is likely to require some clinical phenotyping for patient stratification. Better biomarkers, especially reliable, cost-effective, non-invasive biomarkers with evidenced specificity for VCID, could be implemented into clinical trials and eventually clinical practice. They will leverage risk stratification and fine tuning of therapies. Plasma biomarkers, such as some investigated in MarkVCID, are promising candidates.

*Are SPRINT-MIND findings applicable in LMIC healthcare systems?*

The burden of hypertension is rapidly rising in LMIC and the prevalence is higher compared to high income countries (HIC). There is a wide treatment gap for hypertension and only a minority of hypertensives in LMIC receive treatment, due to low awareness, poor socioeconomic status, limited access to healthcare services and poor treatment adherence51. Therefore, there is a large population at risk of VCID, reflected in the higher prevalence of vascular dementia diagnoses in LMIC. Robust evidence for the benefits of BP lowering and reducing risk of VCID in this large vulnerable population is lacking. There is observational evidence regarding natural history of hypertension and other vascular diseases in LMIC, and some well-characterised longitudinal cohorts of persons with vascular disease have been established. The majority of trials examining vascular risk factor control on dementia risk - including SPRINT-MIND - are conducted in HIC and may not represent global diverse populations7. While there is increasing government support and clinical research to reduce the burden of hypertension through public health programs52 and multicentre studies, there are still challenges for implementation of clinical trials comparable to SPRINT-MIND in LMIC53, 54 (see Table 3). Nevertheless, management of hypertension does appear cost-effective even in resource poor settings across various LMICs22 and therefore feasible to test as a dementia prevention strategy.

*Summary*. Clinical trials such as SPRINT-MIND demonstrating the impact of BP control have enormous potential to benefit cognitive outcomes in the context of LMIC. First, they may be fundamental to developing evidence to influence policy. Second, they may lead to population-based strategies to reduce burden of VCID and dementia globally.

**Table 3. Challenges for Blood Pressure lowering studies in LMIC \*\*\*\*\*\* near here**

*Are particular classes of antihypertensive drugs more beneficial for brain health and cognitive outcomes?*

Meta-analyses of data from large observational cohorts19, 20 support the notion that antihypertensive therapy may help prevent cognitive decline. One meta-analysis of individual patient data of 6 prospective community-based cohort studies, including over 31,000 participants, showed that antihypertensive treatment significantly reduced dementia risk, but found no evidence for one drug class being more efficient than others (Figure 1)19. Another, larger meta-analysis including 27 studies and over 50,000 participants also found no consistent pattern to support any one antihypertensive drug class in cognitive decline or incident dementia20.

Single study evidence has suggested that CCBs or ARBs may particularly reduce dementia risk. The Systolic Hypertension in Europe (SYST-EUR) trial achieved the biggest reduction in incidence of dementia (by 50%) with a CCB55, while trials with other drug types showed no or only modest benefits56-59. An observational study suggested that healthy older adults and MCI patients taking ARBs had larger hippocampal volume, less atrophy, and better cognition compared to patients treated with ACE inhibitors60 although these beneficial effects were not echoed by a trial in mild to moderate AD showing no cognitive benefits of ARB treatment58. ARBs have a good blood-brain barrier penetration and may enhance the catabolism and clearance of Aβ. CCBs have a good blood-brain barrier penetration as well, have neuroprotective effects61 and may reduce  BP variability62. The emerging importance of BP variability in subclinical SVD63 and dementia onset may reveal preferential class effects of certain BP lowering medications over others. As the benefit of BP lowering is likely to reflect several causal factors (as in other diseases e.g. chronic heart failure, chronic kidney disease) a holistic view of multiple pathways appears warranted.

Since SVD progression is likely to underlie dementia risk, a post-hoc analysis of SPRINT-MIND drugs and SVD was carried out64. Use of ACE inhibitors (β, −0.14 [95% CI, −0.23 to −0.04]; P=0.002) and ARBs (β, −0.14 [95% CI, −0.263 to −0.05]; P=0.003) had a small negative association with WML progression, while dihyropyridine calcium channel blockers showed mixed effects in logistic and linear models64. These observational findings suggest there may be a modest class-specific pleiotropic effect of antihypertensive therapy on SVD progression.

*Summary*. Currently there is no convincing evidence that one antihypertensive drug class affords a larger reduction of dementia risk over another. These findings support clinical freedom in the selection of type of antihypertensive drugs to achieve BP goals. The possible protective effects of antihypertensive drugs in prodromal stages of neurodegeneration merits further exploration in prospective outcome-based studies.

***Figure 1. Associations of specific antihypertensive medication use with incident dementia in persons with high blood pressure.****\*\*\*\* near here*

*Should a VCID trial recruit the oldest-old (aged 80+)?*

The significant treatment effect detected in SPRINT-MIND was particularly evident in older participants (aged >70), though this positive finding may be driven by higher event rates in older people (Figure 2). Older adults without pre-existing MCI did well in SPRINT-MIND and their overall adverse event rate did not differ between the treatment groups. This included careful monitoring of kidney function. Specifically, most cases of incident MCI or dementia (and most of the risk reduction) occurred in patients aged >75 years15, 65, supporting the safety of this intervention in older people. We speculate that in older patients at risk for dementia, cardiovascular events (stroke, myocardial infarction, vascular surgery or other cardiovascular interventions) may trigger delirium, and this in turn could progress to cognitive decline66, 67. Prevention of cardiovascular events may therefore contribute to prevention of dementia in this indirect pathway. Prevalence of hypertension, as well as incidence of CVD and dementia, is highest in older adult populations, so treatment is especially important for them.

*Summary*. Trials of VCID should be designed to include the oldest old. This age group may be instrumental for detection of treatment effects of intensive BP lowering.

**Figure 2. Risk reduction across the age range in SPRINT-MIND.** \*\*\*\*\* Near here

*Should inclusion criteria be broad or narrow?*

More crudely, should we lump or split? Lack of external validity of clinical trials can hamper the transportability of clinical trial results to practice. The perception by physicians that certain patient groups are under-represented in research studies is an important cause for under-use of effective treatments. Hence, there is a need to diversify the pool of individuals included in trials. Beneficial effects of BP lowering on cognition may be dependent on patient characteristics (race, comorbidities, cognitive status) or setting (primary care, memory or stroke clinic). A typical older adult at risk of dementia has multiple comorbidities, all potentially modifying treatment efficacy. Hence larger samples are needed to confirm benefit in those most affected. In addition to age, sex, education and *APOE-ε4* status, trajectories of disease progression may differ by race/ethnicity and respond differently to treatment68. Broad and proportional inclusion criteria would potentially avoid replicating findings in different populations. It may be more efficient to use the established machinery of a large trial (recruitment resources, trained staff, equipment, start-up funding) to address a question of diversity, than to launch entirely new studies.

Nonetheless, in view of anticipated clinical benefit, there are valid reasons to exclude individuals who are not at risk for the outcome measure of interest. Examples include those with limited life expectancy (such as nursing home residents) or healthy young persons who have no probability of contributing data to the trial outcomes. Inclusion of participants with high BP or evidence of cerebral SVD at baseline will increase trial power (analogous to screening patients for β-amyloid-positive status, for inclusion in trials of amyloid lowering therapy).

Several counter-arguments complicate this strategy. First, benefits of BP lowering on CVD outcomes are clear in persons within the normal range of BP69, supporting potential benefits in a wider population at risk of cognitive decline. Second, the need for early intervention favours inclusion of individuals before symptoms of vascular disease become manifest. With the advent of blood tests for AD markers (Aβ peptides, ptau-181, 217 or 231) we may be able to detect nascent AD pathology, alongside vascular risk, in individuals while still cognitively normal. Third, randomised assessment of treatment efficacy may not be feasible or ethical in those with other strong indications for treatment (such as acute cardiovascular events). Broad inclusivity in the design of forthcoming trials will benefit external validity and facilitate subgroup analyses of diverse clinical profiles and racial/ethnic background. SPRINT-MIND did not detect differences between pre-specified ethnic subgroups, and was not powered to do so.

*Summary*. There is a need to diversify the pool of individuals included in clinical trials. Diversification based on age, sex, education and *APOE-ε4* status, alongside race, is critical as these factors may influence treatment response. Recruitment strategies should carefully consider the selection of participants in whom treatment efficacy can be demonstrated during the course of the trial. These should be weighed against effects of restricted inclusion on external validity, and consequent lack of implementation of trial findings in routine clinical practice.

*Would a combined approach that includes lifestyle (not just drugs) be more effective?*

In high-risk populations an intervention based on tailored exercise alone may be beneficial for SVD and cognitive outcomes, although the available data are mixed70, 71. Such lifestyle interventions may be enhanced by expanding to multidomain approaches (physical activity, diet, cognitive engagement, and vascular risk factor management)72 and could potentially maximize the benefits of pharmacological interventions. Current guidelines for management of hypertension already favour such a combined approach73 and this could be extended to brain-related outcomes.

For individuals with cognitive impairment and CVD risk factors, a multidomain intervention may improve executive function, memory and learning, with additional reduction in BP74. In a small study of participants who already had an AD dementia diagnosis, a multidomain intervention was associated with reduced WML progression75. Among dementia-free older adults, a much larger trial of a multidomain intervention (PreDIVA) showed no difference in all-cause dementia, but detected a positive effect on non-AD dementia favouring the intervention group76.

Beyond direct effects on cognition, exercise interventions can improve other determinants of cognitive function, such as mood regulation and physical mobility77, 78, while pharmacological treatment could exert specific effects in managing chronic illness and reducing overall risk. This is important as lifestyle interventions alone did not lead to significant changes in CVD risk markers in the FINGER trial (BP, serum total cholesterol, fasting plasma glucose)72.

Implementation and long-term sustainability of combined interventions may be challenging, especially in ethnically-diverse populations, due to differences in dietary patterns, socioeconomic status, geographical location and accessibility. The ongoing World-Wide FINGERS trial (including its US-based component POINTER) will be critical, as it addresses the implementation barriers in diverse populations. World-Wide FINGERS is testing a multifactorial intervention to reduce the risk for cognitive decline, based on the original FINGERS trial (based in Finland)72 which showed cognitive benefit of a multifactorial intervention. General recommendations for multidomain trials were reviewed in an expert perspective79).

*Summary*. With the success of SPRINT-MIND and growing evidence for the efficacy of lifestyle interventions, a combined approach seems pragmatic in dementia prevention. This multifactorial approach holds promise for additive effects on brain function, ultimately reducing dementia risk. Significant effort and funding will be necessary to perform definitive trials of these combined approaches, considering the complex implementation logistics and long-term sustainability.

*Is it unethical to include a control group without intensive BP lowering in future trials?*

This is a challenging question. On one hand, a clinical trial should have a control group, and a randomisation procedure to assign participants either to intervention or to control treatment. On the other hand, the beneficial effects of intensive BP lowering are clear in terms of mortality and major CVD (as evidenced by the main outcomes of SPRINT16, 44). Hence investigators (and ethical review boards) may be reluctant to have participants assigned to an untreated control group. A control group treated with the national, accepted standard of care is more acceptable.

*Summary*. We agreed that it would be unethical to use a no-treatment control group, and that intensive BP treatment can be appropriately compared to a control group treated with standard of care.

**Concluding Remarks**

Hindsight gets paradoxically clearer with time. SPRINT-MIND gave justified optimism for future cognitive trials. Since 2010, when SPRINT opened, we have learned a lot from SPRINT and other BP-lowering studies. There are numerous points where a future trial would be designed differently. We offer the following take-home messages. 1) Intensive BP lowering with cardiovascular medicines can achieve substantial decline in MCI/dementia risk. This is a foundation to build on. 2) In real-world clinical management, there is a need for early intervention, before symptoms of cognitive decline become manifest. 3) Future study design should include flexibility to adapt to early termination, while maintaining statistical power to determine effects on cognitive endpoints (including dementia incidence). 4) Dementia biomarkers are a flourishing field. Improved biomarkers will provide better, quantifiable trial endpoints, and also greater understanding of physiological effects and risk mediators. 5) Researchers should be encouraged to work towards local and global generalisability, across socioeconomic and ethnic spectra. This is already in progress in WW-FINGERS. 6) Future studies should investigate specific mechanistic targets, and whether there are antihypertensive drug classes that afford the greatest cognitive protection. 7) Future trials should consider combined interventions, with medication alongside lifestyle change (e.g. exercise, diet, cognitive training, social stimulation, vascular risk monitoring).

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**Author contributions**

Conceptualization: FME, AHH

Ideas: all authors

Writing original draft: AHH

Writing – Review & Editing the final draft: all authors

**Inclusion and diversity statement**

One or more of the authors of this paper self-identifies as an underrepresented ethnic minority in their field of research or within their geographical location. One or more of the authors of this paper self-identifies as a gender minority in their field of research. One or more of the authors of this paper self-identifies as living with a disability.

**Declaration of Interests**

The views expressed in this paper are those of the individual authors.

All authors are members of The Alzheimer's Association International Society to Advance Alzheimer's Research and Treatment (ISTAART). This Perspective arose from a Roundtable discussion on 20/09/2021, hosted by the Vascular Cognitive Disorders Professional Interest Area within ISTAART.

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All other authors declare no competing interests.

**Figure Legends**

**Figure 1. Associations of specific antihypertensive medication use with incident dementia in persons with high blood pressure.**Pooled data from six population cohorts of prospectively recruited community-dwelling adults (N=31,090). Horizontal symbols show HR (mean, 95% confidence interval).The P-values for heterogeneity (p-het) are listed.Adapted from Figure 1 of Ding et al. 202019 by permission from the publisher (Elsevier).

**Figure 2. Risk reduction across the age range in SPRINT-MIND.** The left panel shows the cumulative incidence of cognitive impairment (a composite outcome of mild cognitive impairment or probable dementia) by age in SPRINT-MIND comparing intensive to standard treatment, accounting for the competing risk of death. The absolute risk reduction is greater in older adults (age 70 or older), likely due to higher event rates. The right panel shows estimated overall and age-specific sub-distribution hazard ratio from a Fine-Gray competing risks regression model for cognitive impairment (same composite outcome) in SPRINT-MIND comparing intensive to standard treatment. Relative risk reduction is quite consistent across the age range. Shaded areas denote 95% confidence intervals. Overall sHR = 0.85, 95% C.I. = 0.75-0.97. (NM Pajewski, JD Williamson, unpublished data).

**Tables**

|  |  |
| --- | --- |
| Sponsor | National Heart, Lung, and Blood Institute (NHLBI) |
| Start Date; Completion Date | Oct 2010; July 2016 (for primary outcome measure) |
| Primary Outcome Measures | Number of Participants with First Occurrence of a Myocardial Infarction (MI), Acute Coronary Syndrome (ACS), Stroke, Heart Failure (HF), or CVD Death |
| Secondary Outcome Measures | 1. Number of Participants with All-cause Mortality 2. Number of CKD participants with at least 50% decline from baseline eGFR 3. Participants who developed End Stage Renal Disease 4. Number of Patients with All-cause Dementia. Basic Cognition Screening Battery; then, Extended Cognitive Assessment Battery (ECAB) plus the Functional Assessment Questionnaire (FAQ) for daily living skills. All data were adjudicated by a central panel of dementia experts. 5. Small Vessel Cerebral Ischemic Disease. Change in total white matter lesion volume from baseline; change in total brain volume from baseline. |
| Study Design | Allocation: Randomized Intervention Model: Parallel Assignment Masking: Single (Outcomes Assessor) Primary Purpose: Treatment |
| Intervention | **Arm 1: Intensive control of SBP**  Goal of SBP <120 mm Hg. Use of once-daily antihypertensive agents was encouraged unless alternative frequency is indicated/necessary. One or more medications from the following classes: Angiotensin converting enzyme (ACE)-inhibitors, Angiotensin receptor blockers (ARBs), Direct vasodilators, Thiazide-type diuretics, Loop diuretics, Potassium-sparing diuretics, Beta-blockers, Sustained-release calcium channel blockers (CCBs), Alpha1-receptor blockers, Sympatholytics.  **Arm 2: Standard control of SBP**  Goal of SBP <140 mm Hg. Same medications as Arm 1. |
| Actual Enrolment | 9361 (Target: 9250) |
| Eligibility Criteria | **Inclusion Criteria:**  At least 50 years old, female/male  Systolic blood pressure of   * 130 - 180 mm Hg on 0 or 1 medication * 130 - 170 mm Hg on up to 2 medications * 130 - 160 mm Hg on up to 3 medications * 130 - 150 mm Hg on up to 4 medications   Risk (one or more of the following)   1. Presence of clinical or subclinical cardiovascular disease, other than stroke 2. CKD, defined as eGFR 20-59 ml/min/1.73m2 3. Framingham Risk Score for 10-year CVD risk ≥ 15% 4. Age greater than 75 years   **Exclusion Criteria include:**   * Known secondary cause of hypertension, causing concern regarding safety of the protocol. * One minute standing SBP < 110 mm Hg. * Proteinuria (within the past 6 months) * Arm circumference too large or too small to allow accurate BP measurement * History of stroke (not CE or stenting); or cardiovascular event or procedure, or hospitalization for unstable angina within last 3 months; or diabetes mellitus * polycystic kidney disease; or glomerulonephritis, with immunosuppressive therapy; or end-stage renal disease * Symptomatic heart failure within the past 6 months; or left ventricular ejection fraction < 35% * Living in the same household as a SPRINT participant |

**Table 1. Overview of the SPRINT trial design**

For full details of the SPRINT-MIND trial design, see ClinicalTrials.gov Identifier: NCT01206062 (from clinicaltrials.gov).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Intensive treatment** | **Standard treatment** |  |  |  |
| Adjudicated Cognitive Impairment (N=8563, median follow-up = 5.1 years) | | | | | |
|  | Cases per | Cases per | Hazard Ratio |  |  |
| Outcome | 1000 person-years | 1000 person-years | (95% CI)a | P Value | Reference |
| Probable dementia | 7.2 | 8.6 | 0.83 (0.67-1.04) | 0.10 | Williamson et al. 2019 |
| Mild cognitive impairment | 14.6 | 18.3 | 0.81 (0.69-0.95) | 0.007 |
| Composite of mild cognitive impairment or probable dementia | 20.2 | 24.1 | 0.85 (0.74-0.97) | 0.01 |
| Cognitive decline outcomes (N=2921, median follow-up = 4.1 years) | | | | | |
|  | Yearly | Yearly | Difference |  |  |
| Outcome | Slope (95% CI)b | Slope (95% CI)b | (95% CI) | P Value | Reference |
| Memory domainc | -0.005 | -0.001 | -0.004 | 0.33 | Rapp *et al.* 2020 |
| (-0.01 to 0.001) | (-0.006 to 0.005) | (-0.012 to 0.004) |  |
| Processing domaind | -0.025 | -0.015 | -0.01 | 0.02 |
| (-0.03 to -0.019) | (-0.021 to -0.009) | (-0.017 to -0.002) |  |
| Magnetic Resonance Imaging Outcomes (Baseline N=670, median follow-up = 4.0 years) | | | | | |
|  | Mean Change | Mean Change | Difference |  |  |
| Outcome | (95% CI)e | (95% CI)e | (95% CI) | P Value | Reference |
| White Matter Lesion Volume, cm3 | 0.92 | 1.45 | -0.54 | <0.001 | Williamson et al. 2019; Nasrallah *et al.* 2021; Dolui *et al.* 2022. |
| (0.69 to 1.14) | (1.21 to 1.70) | (-0.87 to -0.20) |  |
| Total Brain Volume, cm3 | -30.60 | -26.9 | -3.7 | 0.006 |
| (-32.3 to -28.8) | (-28.8 to -24.9) | (-6.3 to -1.1) |  |
| Hippocampal volume, cm3 | -0.06 | -0.02 | -0.033 | 0.03 |
| (-0.08 to -0.04) | (-0.05 to 0.00) | (-0.062 to -0.003) |  |
| Whole brain cerebral blood flow, mL/100 g/min | 1.46 | -0.84 | 2.3 | 0.02 |
| (0.08 to 2.83) | (-2.30 to 0.61) | (0.30 to 4.30) |  |

**Table 2. What SPRINT-MIND Showed. Cognitive and MRI Outcomes**.

Footnotes to Table 2:

aIntensive treatment versus standard treatment based on stratified Cox proportional hazards regression model.

bYearly slope assuming a linear trend based on a linear mixed model.

cIncludes the Logical Memory I and II, Modified Rey-Osterrieth Complex Figure (immediate recall), and the Hopkins Verbal Learning Test–Revised (delayed recall).

dIncludes the Trail Making Test (parts A and B) and Digit Symbol Coding.

eFor MRI outcomes, change estimates at 3.98 years post-randomization based on a linear mixed model minimally adjusting for intracranial volume and days since randomization, including random effects for participant and imaging facility. Estimates for white matter lesion volume are based on a robust mixed model formulation given the skewed distribution of that outcome. Estimates for hippocampal volume and CBF also adjusted for age and sex.

|  |  |
| --- | --- |
| **Category** | **Challenge** |
| Risk stratification | Well-characterised cohorts of individuals with hypertension and other vascular risk factors are needed across LMIC. |
| Socio-demographics | Differences in sociodemographic profiles between LMIC and HIC populations are likely to impact design and outcomes of clinical trials (Alladi et al., 2018). |
| Life-expectancy | Life-expectancy is lower in LMIC compared to HIC, changing the age profile of participants, see World Bank data: <https://data.worldbank.org/indicator/SP.DYN.LE00.IN> |
| High comorbidity burden | The high burden of coexistent vascular risk factors, including untreated diabetes, metabolic syndrome, dietary factors and cigarette smoking, must be considered in developing trial-specific cohorts. |
| Cognitive assessment | Trials that evaluate cognitive outcomes also require a uniform set of cognitive tests that are validated across diverse populations. Cognitive testing is challenging due to cultural, educational and linguistic diversity. Harmonisation efforts are underway to fill this gap, and validated neuropsychological batteries are now available in multiple languages and for different educational levels (Akinyemi et al., 2021; Iyer et al., 2020). |
| Biomarker standardisation | Imaging and plasma biomarkers of dementia and vascular disease also need to be standardised for diverse populations. |
| Genetic studies | Genetic factors, notably *APOE* genotype, may impact cognitive outcomes and should be systematically incorporated into study design. |
| Infrastructure | Infrastructure to implement trials is needed, including training of clinicians and researchers. |

**Table 3. Challenges for Blood Pressure lowering studies in Lower and Middle Income Countries (LMIC)**

**References**

1. Esiri, M.M., Nagy, Z., Smith, M.Z., Barnetson, L., Smith, A.D. (1999). Cerebrovascular disease and threshold for dementia in the early stages of Alzheimer's disease. Lancet 354, 919-920.

2. Kapasi, A., DeCarli, C., Schneider, J.A. (2017). Impact of multiple pathologies on the threshold for clinically overt dementia. Acta Neuropathol 134, 171-186.

3. Lamar, M., Leurgans, S., Kapasi, A., Barnes, L.L., Boyle, P.A., Bennett, D.A., Arfanakis, K., Schneider, J.A. (2022). Complex Profiles of Cerebrovascular Disease Pathologies in the Aging Brain and Their Relationship With Cognitive Decline. Stroke 53, 218-227.

4. Debette, S., Seshadri, S., Beiser, A., Au, R., Himali, J.J., Palumbo, C., Wolf, P.A., DeCarli, C. (2011). Midlife vascular risk factor exposure accelerates structural brain aging and cognitive decline. Neurology 77, 461-468.

5. Exalto, L.G., Quesenberry, C.P., Barnes, D., Kivipelto, M., Biessels, G.J., Whitmer, R.A. (2014). Midlife risk score for the prediction of dementia four decades later. Alzheimers Dement 10, 562-570.

6. Gorelick, P.B., Scuteri, A., Black, S.E., DeCarli, C., Greenberg, S.M., Iadecola, C., Launer, L.J., Laurent, S., Lopez, O.L., Nyenhuis, D., et al. (2011). Vascular contributions to cognitive impairment and dementia: a statement for healthcare professionals from the american heart association/american stroke association. Stroke 42, 2672-2713.

7. Mooldijk, S.S., Licher, S., Wolters, F.J. (2021). Characterizing Demographic, Racial, and Geographic Diversity in Dementia Research: A Systematic Review. JAMA Neurol 78, 1255-1261.

8. Alladi, S., Hachinski, V. (2018). World dementia: One approach does not fit all. Neurology 91, 264-270.

9. Wolters, F.J., Chibnik, L.B., Waziry, R., Anderson, R., Berr, C., Beiser, A., Bis, J.C., Blacker, D., Bos, D., Brayne, C., et al. (2020). Twenty-seven-year time trends in dementia incidence in Europe and the United States: The Alzheimer Cohorts Consortium. Neurology 95, e519-e531.

10. Bruck, C.C., Wolters, F.J., Ikram, M.A., de Kok, I. (2022). Projected prevalence and incidence of dementia accounting for secular trends and birth cohort effects: a population-based microsimulation study. Eur J Epidemiol

11. Budd Haeberlein, S., Aisen, P.S., Barkhof, F., Chalkias, S., Chen, T., Cohen, S., Dent, G., Hansson, O., Harrison, K., von Hehn, C., et al. (2022). Two Randomized Phase 3 Studies of Aducanumab in Early Alzheimer's Disease. J Prev Alzheimers Dis 9, 197-210.

12. van Dyck, C.H., Swanson, C.J., Aisen, P., Bateman, R.J., Chen, C., Gee, M., Kanekiyo, M., Li, D., Reyderman, L., Cohen, S., et al. (2023). Lecanemab in Early Alzheimer's Disease. N Engl J Med 388, 9-21.

13. Smith, E.E., Cieslak, A., Barber, P., Chen, J., Chen, Y.W., Donnini, I., Edwards, J.D., Frayne, R., Field, T.S., Hegedus, J., et al. (2017). Therapeutic Strategies and Drug Development for Vascular Cognitive Impairment. J. Am. Heart Assoc 6,

14. Hainsworth, A.H., Elahi, F.M., Corriveau, R.A. (2021). An introduction to therapeutic approaches to vascular cognitive impairment. Cereb Circ Cogn Behav 2, 100033.

15. Williamson, J.D., Pajewski, N.M., Auchus, A.P., Bryan, R.N., Chelune, G., Cheung, A.K., Cleveland, M.L., Coker, L.H., Crowe, M.G., Cushman, W.C., et al. (2019). Effect of Intensive vs Standard Blood Pressure Control on Probable Dementia: A Randomized Clinical Trial. JAMA 321, 553-561.

16. Wright, J.T., Jr., Williamson, J.D., Whelton, P.K., Snyder, J.K., Sink, K.M., Rocco, M.V., Reboussin, D.M., Rahman, M., Oparil, S., Lewis, C.E., et al. (2015). A Randomized Trial of Intensive versus Standard Blood-Pressure Control. N Engl J Med 373, 2103-2116.

17. Peters, R., Beckett, N., McCormack, T., Fagard, R., Fletcher, A., Bulpitt, C. (2014). Treating hypertension in the very elderly-benefits, risks, and future directions, a focus on the hypertension in the very elderly trial. Eur Heart J 35, 1712-1718.

18. Peters, R., Xu, Y., Fitzgerald, O., Aung, H.L., Beckett, N., Bulpitt, C., Chalmers, J., Forette, F., Gong, J., Harris, K., et al. (2022). Blood pressure lowering and prevention of dementia: an individual patient data meta-analysis. Eur Heart J 43, 4980-4990.

19. Ding, J., Davis-Plourde, K.L., Sedaghat, S., Tully, P.J., Wang, W., Phillips, C., Pase, M.P., Himali, J.J., Gwen Windham, B., Griswold, M., et al. (2019). Antihypertensive medications and risk for incident dementia and Alzheimer's disease: a meta-analysis of individual participant data from prospective cohort studies. Lancet Neurol

20. Peters, R., Yasar, S., Anderson, C.S., Andrews, S., Antikainen, R., Arima, H., Beckett, N., Beer, J.C., Bertens, A.S., Booth, A., et al. (2020). Investigation of antihypertensive class, dementia, and cognitive decline: A meta-analysis. Neurology 94, e267-e281.

21. Lim, S.S., Gaziano, T.A., Gakidou, E., Reddy, K.S., Farzadfar, F., Lozano, R., Rodgers, A. (2007). Prevention of cardiovascular disease in high-risk individuals in low-income and middle-income countries: health effects and costs. Lancet 370, 2054-2062.

22. Kostova, D., Spencer, G., Moran, A.E., Cobb, L.K., Husain, M.J., Datta, B.K., Matsushita, K., Nugent, R. (2020). The cost-effectiveness of hypertension management in low-income and middle-income countries: a review. BMJ Glob Health 5,

23. van Rijssel, A.E., Stins, B.C., Beishon, L.C., Sanders, M.L., Quinn, T.J., Claassen, J., de Heus, R.A.A. (2022). Effect of Antihypertensive Treatment on Cerebral Blood Flow in Older Adults: a Systematic Review and Meta-Analysis. Hypertension HYPERTENSIONAHA12118255.

24. Licher, S., Heshmatollah, A., van der Willik, K.D., Stricker, B.H.C., Ruiter, R., de Roos, E.W., Lahousse, L., Koudstaal, P.J., Hofman, A., Fani, L., et al. (2019). Lifetime risk and multimorbidity of non-communicable diseases and disease-free life expectancy in the general population: A population-based cohort study. PLoS Med 16, e1002741.

25. Rapp, S.R., Gaussoin, S.A., Sachs, B.C., Chelune, G., Supiano, M.A., Lerner, A.J., Wadley, V.G., Wilson, V.M., Fine, L.J., Whittle, J.C., et al. (2020). Effects of intensive versus standard blood pressure control on domain-specific cognitive function: a substudy of the SPRINT randomised controlled trial. Lancet Neurol 19, 899-907.

26. Alber, J., Alladi, S., Bae, H.J., Barton, D.A., Beckett, L.A., Bell, J.M., Berman, S.E., Biessels, G.J., Black, S.E., Bos, I., et al. (2019). White matter hyperintensities in vascular contributions to cognitive impairment and dementia (VCID): Knowledge gaps and opportunities. Alzheimers Dement (N Y) 5, 107-117.

27. Dolui, S., Detre, J.A., Gaussoin, S.A., Herrick, J.S., Wang, D.J.J., Tamura, M.K., Cho, M.E., Haley, W.E., Launer, L.J., Punzi, H.A., et al. (2022). Association of Intensive vs Standard Blood Pressure Control With Cerebral Blood Flow: Secondary Analysis of the SPRINT MIND Randomized Clinical Trial. JAMA Neurol

28. Nasrallah, I.M., Gaussoin, S.A., Pomponio, R., Dolui, S., Erus, G., Wright, C.B., Launer, L.J., Detre, J.A., Wolk, D.A., Davatzikos, C., et al. (2021). Association of Intensive vs Standard Blood Pressure Control With Magnetic Resonance Imaging Biomarkers of Alzheimer Disease: Secondary Analysis of the SPRINT MIND Randomized Trial. JAMA Neurol 78, 568-577.

29. Nasrallah, I.M., Pajewski, N.M., Auchus, A.P., Chelune, G., Cheung, A.K., Cleveland, M.L., Coker, L.H., Crowe, M.G., Cushman, W.C., Cutler, J.A., et al. (2019). Association of Intensive vs Standard Blood Pressure Control With Cerebral White Matter Lesions. JAMA 322, 524-534.

30. Murray, A.M., Hsu, F.C., Williamson, J.D., Bryan, R.N., Gerstein, H.C., Sullivan, M.D., Miller, M.E., Leng, I., Lovato, L.L., Launer, L.J., et al. (2017). ACCORDION MIND: results of the observational extension of the ACCORD MIND randomised trial. Diabetologia 60, 69-80.

31. Jaeger, B.C., Bress, A.P., Bundy, J.D., Cheung, A.K., Cushman, W.C., Drawz, P.E., Johnson, K.C., Lewis, C.E., Oparil, S., Rocco, M.V., et al. (2022). Longer-Term All-Cause and Cardiovascular Mortality With Intensive Blood Pressure Control: A Secondary Analysis of a Randomized Clinical Trial. JAMA Cardiol 7, 1138-1146.

32. Lockhart, S.N., Schaich, C.L., Craft, S., Sachs, B.C., Rapp, S.R., Jung, Y., Whitlow, C.T., Solingapuram Sai, K.K., Cleveland, M., Williams, B.J., et al. (2022). Associations among vascular risk factors, neuroimaging biomarkers, and cognition: Preliminary analyses from the Multi-Ethnic Study of Atherosclerosis (MESA). Alzheimers Dement 18, 551-560.

33. Lu, H., Kashani, A.H., Arfanakis, K., Caprihan, A., DeCarli, C., Gold, B.T., Li, Y., Maillard, P., Satizabal, C.L., Stables, L., et al. (2021). MarkVCID cerebral small vessel consortium: II. Neuroimaging protocols. Alzheimers Dement 17, 716-725.

34. Wilcock, D., Jicha, G., Blacker, D., Albert, M.S., D'Orazio, L.M., Elahi, F.M., Fornage, M., Hinman, J.D., Knoefel, J., Kramer, J., et al. (2021). MarkVCID cerebral small vessel consortium: I. Enrollment, clinical, fluid protocols. Alzheimers Dement 17, 704-715.

35. Smith, E.E., Biessels, G.J., De Guio, F., de Leeuw, F.E., Duchesne, S., During, M., Frayne, R., Ikram, M.A., Jouvent, E., MacIntosh, B.J., et al. (2019). Harmonizing brain magnetic resonance imaging methods for vascular contributions to neurodegeneration. Alzheimers Dement (Amst) 11, 191-204.

36. Baykara, E., Gesierich, B., Adam, R., Tuladhar, A.M., Biesbroek, J.M., Koek, H.L., Ropele, S., Jouvent, E., Alzheimer's Disease Neuroimaging, I., Chabriat, H., et al. (2016). A Novel Imaging Marker for Small Vessel Disease Based on Skeletonization of White Matter Tracts and Diffusion Histograms. Ann Neurol 80, 581-592.

37. Chalmers, J., Neal, B., MacMahon, S., Committee, P.M. (2000). PROGRESS (Perindopril Protection Against Recurrent Stroke Study): regional characteristics of the study population at baseline. PROGRESS Management Committee. J Hypertens Suppl 18, S13-19.

38. Cunningham, E.L., Todd, S.A., Passmore, P., Bullock, R., McGuinness, B. (2021). Pharmacological treatment of hypertension in people without prior cerebrovascular disease for the prevention of cognitive impairment and dementia. Cochrane Database Syst Rev 5, CD004034.

39. Sabayan, B., Oleksik, A.M., Maier, A.B., van Buchem, M.A., Poortvliet, R.K., de Ruijter, W., Gussekloo, J., de Craen, A.J., Westendorp, R.G. (2012). High blood pressure and resilience to physical and cognitive decline in the oldest old: the Leiden 85-plus Study. J Am Geriatr Soc 60, 2014-2019.

40. DeCarli, C., Miller, B.L., Swan, G.E., Reed, T., Wolf, P.A., Garner, J., Jack, L., Carmelli, D. (1999). Predictors of brain morphology for the men of the NHLBI twin study. Stroke 30, 529-536.

41. Claassen, J., Thijssen, D.H.J., Panerai, R.B., Faraci, F.M. (2021). Regulation of cerebral blood flow in humans: physiology and clinical implications of autoregulation. Physiol Rev 101, 1487-1559.

42. de Heus, R.A.A., de Jong, D.L.K., Sanders, M.L., van Spijker, G.J., Oudegeest-Sander, M.H., Hopman, M.T., Lawlor, B.A., Olde Rikkert, M.G.M., Claassen, J. (2018). Dynamic Regulation of Cerebral Blood Flow in Patients With Alzheimer Disease. Hypertension 72, 139-150.

43. Tryambake, D., He, J., Firbank, M.J., O'Brien, J.T., Blamire, A.M., Ford, G.A. (2013). Intensive blood pressure lowering increases cerebral blood flow in older subjects with hypertension. Hypertension 61, 1309-1315.

44. Lewis, C.E., Fine, L.J., Beddhu, S., Cheung, A.K., Cushman, W.C., Cutler, J.A., Evans, G.W., Johnson, K.C., Kitzman, D.W., Oparil, S., et al. (2021). Final Report of a Trial of Intensive versus Standard Blood-Pressure Control. N Engl J Med 384, 1921-1930.

45. Juraschek, S.P., Hu, J.R., Cluett, J.L., Ishak, A., Mita, C., Lipsitz, L.A., Appel, L.J., Beckett, N.S., Coleman, R.L., Cushman, W.C., et al. (2021). Effects of Intensive Blood Pressure Treatment on Orthostatic Hypotension : A Systematic Review and Individual Participant-based Meta-analysis. Ann Intern Med 174, 58-68.

46. Juraschek, S.P., Taylor, A.A., Wright, J.T., Jr., Evans, G.W., Miller, E.R., 3rd, Plante, T.B., Cushman, W.C., Gure, T.R., Haley, W.E., Moinuddin, I., et al. (2020). Orthostatic Hypotension, Cardiovascular Outcomes, and Adverse Events: Results From SPRINT. Hypertension 75, 660-667.

47. de Heus, R.A.A., Donders, R., Santoso, A.M.M., Olde Rikkert, M.G.M., Lawlor, B.A., Claassen, J., Nilvad Study, G. (2019). Blood Pressure Lowering With Nilvadipine in Patients With Mild-to-Moderate Alzheimer Disease Does Not Increase the Prevalence of Orthostatic Hypotension. J Am Heart Assoc 8, e011938.

48. Elahi, F.M., Harvey, D., Altendahl, M., Brathaban, N., Fernandes, N., Casaletto, K.B., Staffaroni, A.M., Maillard, P., Hinman, J.D., Miller, B.L., et al. (2021). Elevated complement mediator levels in endothelial-derived plasma exosomes implicate endothelial innate inflammation in diminished brain function of aging humans. Sci Rep 11, 16198.

49. Pauls, M.M., Binnie, L.R., Benjamin, P., Betteridge, S., Clarke, B., Dhillon, M., Ghatala, R., Hainsworth, F., Howe, F.A., Khan, U., et al. (2022). The PASTIS trial. Testing tadalafil for possible use in vascular cognitive impairment Alzheimers & Dementia in press,

50. Blair, G.W., Appleton, J.P., Law, Z.K., Doubal, F., Flaherty, K., Dooley, R., Shuler, K., Richardson, C., Hamilton, I., Shi, Y., et al. (2018). Preventing cognitive decline and dementia from cerebral small vessel disease: The LACI-1 Trial. Protocol and statistical analysis plan of a phase IIa dose escalation trial testing tolerability, safety and effect on intermediary endpoints of isosorbide mononitrate and cilostazol, separately and in combination. Int J Stroke 13, 530-538.

51. Anchala, R., Kannuri, N.K., Pant, H., Khan, H., Franco, O.H., Di Angelantonio, E., Prabhakaran, D. (2014). Hypertension in India: a systematic review and meta-analysis of prevalence, awareness, and control of hypertension. J Hypertens 32, 1170-1177.

52. Tian, M., Ajay, V.S., Dunzhu, D., Hameed, S.S., Li, X., Liu, Z., Li, C., Chen, H., Cho, K., Li, R., et al. (2015). A Cluster-Randomized, Controlled Trial of a Simplified Multifaceted Management Program for Individuals at High Cardiovascular Risk (SimCard Trial) in Rural Tibet, China, and Haryana, India. Circulation 132, 815-824.

53. Akinyemi, R.O., Yaria, J., Ojagbemi, A., Guerchet, M., Okubadejo, N., Njamnshi, A.K., Sarfo, F.S., Akpalu, A., Ogbole, G., Ayantayo, T., et al. (2021). Dementia in Africa: Current evidence, knowledge gaps, and future directions. Alzheimers Dement

54. Iyer, G.K., Paplikar, A., Alladi, S., Dutt, A., Sharma, M., Mekala, S., Kaul, S., Saroja, A.O., Divyaraj, G., Ellajosyula, R., et al. (2020). Standardising Dementia Diagnosis Across Linguistic and Educational Diversity: Study Design of the Indian Council of Medical Research-Neurocognitive Tool Box (ICMR-NCTB). J Int Neuropsychol Soc 26, 172-186.

55. Forette, F., Seux, M.L., Staessen, J.A., Thijs, L., Birkenhager, W.H., Babarskiene, M.R., Babeanu, S., Bossini, A., Gil-Extremera, B., Girerd, X., et al. (1998). Prevention of dementia in randomised double-blind placebo-controlled Systolic Hypertension in Europe (Syst-Eur) trial. Lancet 352, 1347-1351.

56. Diener, H.C., Sacco, R.L., Yusuf, S., Cotton, D., Ounpuu, S., Lawton, W.A., Palesch, Y., Martin, R.H., Albers, G.W., Bath, P., et al. (2008). Effects of aspirin plus extended-release dipyridamole versus clopidogrel and telmisartan on disability and cognitive function after recurrent stroke in patients with ischaemic stroke in the Prevention Regimen for Effectively Avoiding Second Strokes (PRoFESS) trial: a double-blind, active and placebo-controlled study. Lancet Neurol 7, 875-884.

57. Anderson, C., Teo, K., Gao, P., Arima, H., Dans, A., Unger, T., Commerford, P., Dyal, L., Schumacher, H., Pogue, J., et al. (2011). Renin-angiotensin system blockade and cognitive function in patients at high risk of cardiovascular disease: analysis of data from the ONTARGET and TRANSCEND studies. Lancet Neurol 10, 43-53.

58. Kehoe, P.G., Turner, N., Howden, B., Jarutyte, L., Clegg, S.L., Malone, I.B., Barnes, J., Nielsen, C., Sudre, C.H., Wilson, A., et al. (2021). Safety and efficacy of losartan for the reduction of brain atrophy in clinically diagnosed Alzheimer's disease (the RADAR trial): a double-blind, randomised, placebo-controlled, phase 2 trial. Lancet Neurol 20, 895-906.

59. Peters, R., Dodge, H.H., James, S., Jicha, G.A., Meyer, P.F., Richards, M., Smith, A.D., Yassine, H.N., Abner, E., Hainsworth, A.H., et al. (2021). The epidemiology is promising, but the trial evidence is weak. Why pharmacological dementia risk reduction trials haven't lived up to expectations, and where do we go from here? Alzheimers Dement

60. Edwards, J.D., Ramirez, J., Callahan, B.L., Tobe, S.W., Oh, P., Berezuk, C., Lanctot, K., Swardfager, W., Nestor, S., Kiss, A., et al. (2017). Antihypertensive Treatment is associated with MRI-Derived Markers of Neurodegeneration and Impaired Cognition: A Propensity-Weighted Cohort Study. J Alzheimers Dis 59, 1113-1122.

61. Trompet, S., Westendorp, R.G., Kamper, A.M., de Craen, A.J. (2008). Use of calcium antagonists and cognitive decline in old age. The Leiden 85-plus study. Neurobiol Aging 29, 306-308.

62. Webb, A.J., Fischer, U., Mehta, Z., Rothwell, P.M. (2010). Effects of antihypertensive-drug class on interindividual variation in blood pressure and risk of stroke: a systematic review and meta-analysis. Lancet 375, 906-915.

63. Ma, Y., Blacker, D., Viswanathan, A., van Veluw, S.J., Bos, D., Vernooij, M.W., Hyman, B.T., Tzourio, C., Das, S., Hofman, A. (2021). Visit-to-Visit Blood Pressure Variability, Neuropathology, and Cognitive Decline. Neurology 96, e2812-e2823.

64. Goldstein, E.D., Wolcott, Z., Garg, G., Navarro, K., Delic, A., Yaghi, S., Sederholm, B., Prabhakaran, S., Wong, K.H., McLean, K., et al. (2022). Effect of Antihypertensives by Class on Cerebral Small Vessel Disease: A Post Hoc Analysis of SPRINT-MIND. Stroke 101161STROKEAHA121037997.

65. Pajewski, N.M., Berlowitz, D.R., Bress, A.P., Callahan, K.E., Cheung, A.K., Fine, L.J., Gaussoin, S.A., Johnson, K.C., King, J., Kitzman, D.W., et al. (2020). Intensive vs Standard Blood Pressure Control in Adults 80 Years or Older: A Secondary Analysis of the Systolic Blood Pressure Intervention Trial. J Am Geriatr Soc 68, 496-504.

66. Pereira, J.V., Aung Thein, M.Z., Nitchingham, A., Caplan, G.A. (2021). Delirium in older adults is associated with development of new dementia: a systematic review and meta-analysis. Int J Geriatr Psychiatry 36, 993-1003.

67. Richardson, S.J., Davis, D.H.J., Stephan, B.C.M., Robinson, L., Brayne, C., Barnes, L.E., Taylor, J.P., Parker, S.G., Allan, L.M. (2021). Recurrent delirium over 12 months predicts dementia: results of the Delirium and Cognitive Impact in Dementia (DECIDE) study. Age Ageing 50, 914-920.

68. Rizvi, B., Lao, P.J., Chesebro, A.G., Dworkin, J.D., Amarante, E., Beato, J.M., Gutierrez, J., Zahodne, L.B., Schupf, N., Manly, J.J., et al. (2021). Association of Regional White Matter Hyperintensities With Longitudinal Alzheimer-Like Pattern of Neurodegeneration in Older Adults. JAMA Netw Open 4, e2125166.

69. Blood Pressure Lowering Treatment Trialists, C. (2021). Pharmacological blood pressure lowering for primary and secondary prevention of cardiovascular disease across different levels of blood pressure: an individual participant-level data meta-analysis. Lancet 397, 1625-1636.

70. Bolandzadeh, N., Tam, R., Handy, T.C., Nagamatsu, L.S., Hsu, C.L., Davis, J.C., Dao, E., Beattie, B.L., Liu-Ambrose, T. (2015). Resistance Training and White Matter Lesion Progression in Older Women: Exploratory Analysis of a 12-Month Randomized Controlled Trial. J Am Geriatr Soc 63, 2052-2060.

71. Liu-Ambrose, T., Best, J.R., Davis, J.C., Eng, J.J., Lee, P.E., Jacova, C., Boyd, L.A., Brasher, P.M., Munkacsy, M., Cheung, W., et al. (2016). Aerobic exercise and vascular cognitive impairment: A randomized controlled trial. Neurology 87, 2082-2090.

72. Ngandu, T., Lehtisalo, J., Solomon, A., Levalahti, E., Ahtiluoto, S., Antikainen, R., Backman, L., Hanninen, T., Jula, A., Laatikainen, T., et al. (2015). A 2 year multidomain intervention of diet, exercise, cognitive training, and vascular risk monitoring versus control to prevent cognitive decline in at-risk elderly people (FINGER): a randomised controlled trial. Lancet 385, 2255-2263.

73. Whelton, P.K., Carey, R.M., Aronow, W.S., Casey, D.E., Jr., Collins, K.J., Dennison Himmelfarb, C., DePalma, S.M., Gidding, S., Jamerson, K.A., Jones, D.W., et al. (2018). 2017 ACC/AHA/AAPA/ABC/ACPM/AGS/APhA/ASH/ASPC/NMA/PCNA Guideline for the Prevention, Detection, Evaluation, and Management of High Blood Pressure in Adults: Executive Summary: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. Circulation 138, e426-e483.

74. Blumenthal, J.A., Smith, P.J., Mabe, S., Hinderliter, A., Welsh-Bohmer, K., Browndyke, J.N., Doraiswamy, P.M., Lin, P.H., Kraus, W.E., Burke, J.R., et al. (2020). Longer Term Effects of Diet and Exercise on Neurocognition: 1-Year Follow-up of the ENLIGHTEN Trial. J Am Geriatr Soc 68, 559-568.

75. Richard, E., Gouw, A.A., Scheltens, P., van Gool, W.A. (2010). Vascular care in patients with Alzheimer disease with cerebrovascular lesions slows progression of white matter lesions on MRI: the evaluation of vascular care in Alzheimer's disease (EVA) study. Stroke 41, 554-556.

76. Moll van Charante, E.P., Richard, E., Eurelings, L.S., van Dalen, J.W., Ligthart, S.A., van Bussel, E.F., Hoevenaar-Blom, M.P., Vermeulen, M., van Gool, W.A. (2016). Effectiveness of a 6-year multidomain vascular care intervention to prevent dementia (preDIVA): a cluster-randomised controlled trial. Lancet 388, 797-805.

77. Liu-Ambrose, T., Davis, J.C., Best, J.R., Dian, L., Madden, K., Cook, W., Hsu, C.L., Khan, K.M. (2019). Effect of a Home-Based Exercise Program on Subsequent Falls Among Community-Dwelling High-Risk Older Adults After a Fall: A Randomized Clinical Trial. JAMA 321, 2092-2100.

78. Pahor, M., Guralnik, J.M., Ambrosius, W.T., Blair, S., Bonds, D.E., Church, T.S., Espeland, M.A., Fielding, R.A., Gill, T.M., Groessl, E.J., et al. (2014). Effect of structured physical activity on prevention of major mobility disability in older adults: the LIFE study randomized clinical trial. JAMA 311, 2387-2396.

79. Kivipelto, M., Mangialasche, F., Ngandu, T. (2018). Lifestyle interventions to prevent cognitive impairment, dementia and Alzheimer disease. Nat Rev Neurol 14, 653-666.