Teleneurology and mobile technologies: the future of neurological care

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Abstract | Neurological disorders are the leading cause of global disability. However, for most people around the world, current neurological care is poor. In low-income countries, most individuals lack access to proper neurological care, and in high-income countries, distance and disability limit access. With the global proliferation of smartphones, teleneurology — the use of technology to provide neurological care and education remotely — has the potential to improve and increase access to care for billions of people. Telestroke has already fulfilled this promise, but teleneurology applications for chronic conditions are still in their infancy. Similarly, few studies have explored the capabilities of mobile technologies such as smartphones and wearable sensors, which can guide care by providing objective, frequent, real-world assessments of patients. In low-income settings, teleneurology can increase the capacity of local care systems through professional development, diagnostic support and consultative services. In high-income settings, teleneurology is likely to promote the expansion and migration of neurological care away from institutions, incorporate systems of asynchronous communication (such as e-mail), integrate clinicians with diverse skill sets and reach new populations. Inertia, outdated policies and social barriers — especially the digital divide — will slow this progress at considerable cost. However, a future increasingly will be possible in which neurological care can be accessed by anyone, anywhere. Here, we examine the emerging evidence regarding the benefits of teleneurology for chronic conditions, its role and risks in low-income countries and the promise of mobile technologies to measure disease status and deliver care. We conclude by discussing the future trends, barriers and timing for the adoption of teleneurology.

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The current state of neurological care is poor: large swaths of the world lack access to proper neurological care[1]. In India, nearly 1 billion people live in regions that lack a practising neurologist who is affiliated with a major professional society[2]. Furthermore, the Arab world has only 1 neurologist for every 300,000 individuals[3], and in 23 countries in Africa, the average population per neurologist exceeds 5 million[4]. Consequently, the WHO and the World Federation of Neurology reported that the "available resources for neurological services in most countries of the world are insufficient compared with global need for neurological care" (REF. 1).

Even in high-income nations, access to neurological care is limited. In the USA, more than 40% of individuals with Parkinson disease (PD) over the age of 65 years did not see a neurologist over a 4-year period. Those who do not see a neurologist are more likely to fracture a hip, be placed in a skilled nursing facility or die than those who do[5]. In Europe, 44% of individuals with PD do not see a specialist within 2 years of diagnosis[6]. Even where care is accessible, it is often unsafe[7], delayed[8], inconvenient[9] and inefficient[10]. A 2015 report found that neurological care in the United Kingdom's National Health Service is "fragmented and poorly coordinated across health and social care providers", that "patients admitted with a neurological condition rarely see a neurologist" and that "services are not sustainable in their current form and redesign is needed" (REF. 11).

A new model that can address this care gap is telehealth, which comprises the use of technology to provide health care, education and remote monitoring[12]. In the 20th century, the telephone began to connect geographically separated patients[13,14]; in the 21st century, video conferencing and smartphones have increased the capabilities and availability of telehealth. In addition to these synchronous forms of telehealth in which patients and clinicians connect at the same time, asynchronous forms of telehealth (such as e-mail[15] and remote

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Key points

- Neurological disorders are the leading cause of global disability; however, much of the world lacks access to proper neurological care.
- Teleneurology, the use of technology to provide remote neurological care and education, has immense potential to increase access to care for people around the world.
- Telestroke has realized this potential, and teleneurology applications for chronic conditions are beginning to emerge.
- Mobile technologies, especially smartphones and wearable sensors, can provide objective, frequent assessments of neurological conditions, but applications of these technologies are in their infancy.
- In low-income settings, teleneurology can increase local capabilities through education, diagnostic assistance and consultation.
- In high-income settings, neurological care will expand and migrate from hospitals and clinics to homes and mobile devices, incorporate systems of asynchronous communications and integrate clinicians with diverse skill sets.

monitoring[16,17]) are now possible[18,19]. Store-and-forward techniques, in which clinical information (such as an image, EEG tracing or case history) is collected and then sent to a clinician for review and consultation, represent another common asynchronous method[20]. The use of these telehealth applications for neurological disorders is termed teleneurology.

In this report, we highlight telestroke as a model for teleneurology, review the evidence supporting the use of teleneurology for chronic conditions, consider the role and risks of teleneurology in low-income countries, evaluate the promise of mobile technologies such as smartphones and wearable sensors to measure disease and discuss future trends and barriers for care.

Telestroke as a model for teleneurology

In 1999, Levine and Gorman introduced the concept of telestroke, which uses technology to enable remote neurologists to care for patients with acute stroke in hospitals that lack access to neurologists[21]. Fifteen years later, telestroke had become mainstream practice[22].

The evolution of telestroke could provide some insight as to the development of teleneurology for chronic conditions[22–27]. Different models of telestroke care have evolved, ranging from sending most patients to stroke centres to keeping most patients in satellite hospitals[22], and the capacity of local hospitals around the world to manage acute strokes has increased through improved education and greater experience in caring for patients with acute stroke[28–31]. The scope of stroke services enabled by technology is expanding and now includes multiple rehabilitative services[32]. Telestroke has also moved beyond satellite hospitals to mobile CT-enabled ambulances that bring hospital-level care directly to the patient[33]. Crucially, telestroke has been shown to meet the aims articulated by the US National Academy of Medicine to improve the quality of care[34]: telestroke is safe[35], effective[36], patient-centered[37], timely[38], efficient[39] and equitable[40]. Overall, telestroke has increased access to care for millions of people, and the number of telestroke programmes is expanding throughout the world[31,41,42]. However, despite the progress of telestroke, much work remains. One-quarter of potentially eligible patients in the USA who have an acute stroke fail to receive tissue plasminogen activator[43], and the proportion of individuals who go untreated is much higher elsewhere in the world.

Teleneurology for chronic conditions

The need for teleneurology for the management of chronic conditions is immense. Although the global burden of stroke is increasing, the global burden of chronic neurological disorders is rising even faster[44,45]. Furthermore, the supply of neurologists — especially paediatric neurologists[46] — is limited, and individuals with chronic conditions benefit extensively from their care[47]. Access to care is restricted by distance, patient disability and the distribution of neurologists.

Teleneurology could benefit many with neurological conditions. Many neurological disorders (such as amyotrophic lateral sclerosis and PD) impair mobility, cognitive function and driving ability. As these diseases progress, the ability of the individual to access care decreases, which leaves those with the greatest need for attention receiving the least care. Additionally, rare conditions — especially paediatric disorders — that have dispersed populations and few experts are also well suited for teleneurology[48]. Individuals with neglected tropical diseases, which affect 1.5 billion of the world's most impoverished people, could also benefit from teleneurology, as 30% of these conditions have neurological manifestations[49,50]. Furthermore, remote assessments that enable individuals to remain at home might be preferable for many neurological conditions — from autism to Alzheimer disease (AD)[51].

Despite the need for teleneurology for chronic conditions, these programmes are still in their infancy[52]. Unlike telestroke, adoption of telemedicine for chronic neurological conditions has been slow, although these applications pre-date telestroke[53]. However, the pace of adoption is beginning to change, and the number of studies has risen since 2015 (FIG. 1a).

Randomized controlled trials of teleneurology are also beginning to emerge. These trials[54–62], which thus far have been conducted in high-income countries, cover many neurological conditions, from headaches to multiple sclerosis (TABLE 1). The results have demonstrated that teleneurology is feasible, generates outcomes comparable to usual care and is well liked by patients and clinicians, independent of the types of clinicians involved, the outcome metrics employed and the neurological conditions examined[63,64]. Future trials could seek to demonstrate non-inferiority of clinical outcomes, quantify economic benefits to patients and caregivers, solicit preference of patients for the competing care models and include larger and more representative populations to support broader adoption.

In addition to connecting clinicians to patients, an emerging telehealth model connects remote experts to local clinicians to improve their capacity to treat complex diseases. The Extension for Community Healthcare Outcomes (Project ECHO), which first evaluated outcomes of treatment for hepatitis C in New Mexico, uses

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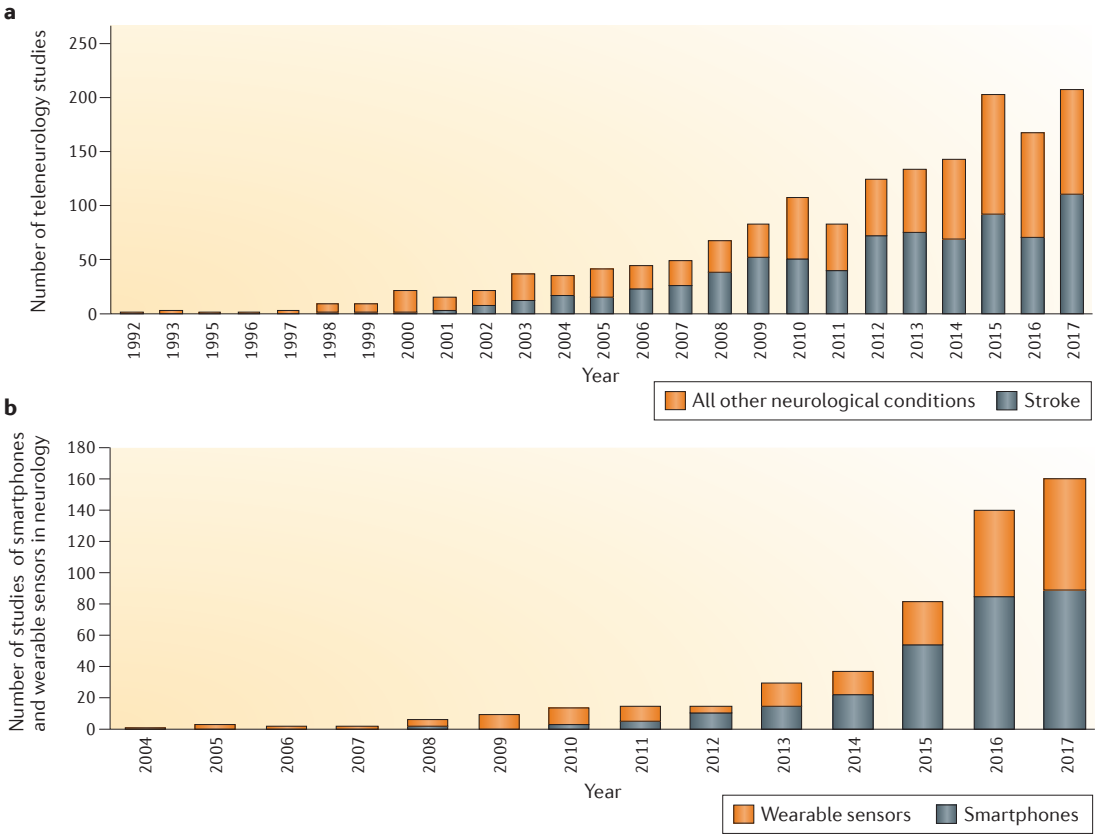

Figure 1 | **Proliferation of teleneurology studies. a** | A graph showing the volume of published studies of telehealth and care delivery for stroke (grey) and other neurological conditions (orange) from 1992 to 2017, as listed on PubMed. The past two decades have seen a substantial increase in the volume of these studies. **b** | A graph showing the volume of published studies of smartphones (grey) and wearable sensors (orange) for neurological conditions from 1992 to 2017, as listed on PubMed. Few studies were conducted before 2015, but the number has since increased exponentially.

video to connect remote specialists with primary-care providers to educate the local clinicians, discuss their cases and provide ongoing educational support[65]. This model has now been extended to dementia care[66,67] and could be valuable for the management of common neurological conditions such as epilepsy, low back pain and migraine. By enhancing the care capacity of local clinicians at low cost[68,69], this model is poised for rapid global growth, especially in resource-limited settings[70].

Despite the promise of teleneurology, concerns remain about its potential adverse effects on the quality of patient–clinician relationships, examination and care[71]. To evaluate these concerns, identification of an appropriate baseline is critical. In many cases, the gold standard for patient-centred care is not the conventional clinic appointment, in which sick patients travel to see healthy clinicians, but the traditional house call, in which clinicians travel to see patients[72]. In other cases, distance can prevent house calls, and the appropriate comparison might be care provided without a neurologist. Finally, for some situations, the appropriate comparison might be no care at all[1,73].

Nevertheless, remote care has its limitations. Engendering trust can be more difficult remotely than in person. However, in a 2017 randomized controlled trial of video visits in a patient's home (so-called virtual house calls), individuals with PD preferred the personal connection with the remote specialist to their local clinician after 1 year[56]. This assessment was conducted after four virtual visits over the course of 1 year, which is likely to have allowed time for comfort and trust to develop between patient and clinician.

In some instances, the quality of a remote examination could be inferior to that of an in-person examination (for example, the assessment of reflexes). However, in other situations, the exam might be better than what would otherwise have occurred (for example, a remote neurologist could support a local emergency room physician). Moreover, standard examinations for stroke[74], movement disorders[75–78] and other neurological disorders[52] can be conducted remotely in a reliable manner. For some conditions in which a detailed exam and diagnostic testing are crucial (such as multiple sclerosis, myasthenia gravis and Duchenne muscular dystrophy), an optimal solution could be an in-person initial evaluation followed by remote longitudinal care[52].

Just as few studies have evaluated the quality of current neurological care[79], few have assessed the quality of teleneurology care[54]. Future studies will probably seek to demonstrate that the quality of teleneurology care is comparable to current models but that teleneurology offers other advantages, such as convenience, patient

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satisfaction and time and travel savings[80]. Conduct of such studies will require reversal of the current substantial underinvestment in the improvement of health and neurological care[81], especially in low-income countries.

Teleneurology in low-income countries

Teleneurology can help to improve care in low-income and middle-income countries where neurological services are limited to tertiary academic medical centres in the country's capital city or major urban centres. In 2004, the WHO reported the median number of postgraduate neurology trainees in the pipeline to be 0 and 4 per year per 10,000,000 people in low-income and lower-middle-income countries, respectively, compared with 15 per year per 10,000,000 people in high-income countries, with most of Africa devoid of postgraduate neurological training[1]. Since that time, repatriation of physician scientists trained abroad and expanded training programmes have helped to seed small neurology divisions around the world[82–84].

Teleneurology is supporting these efforts to increase the capacity of neurological services[85,86]. Specialists in neurology and allied fields who obtain training abroad and return to start programmes in their home countries can have continued support and interactions with global colleagues through regular clinical case conferences and subspecialty consultations[87]. Once collaborative relationships are established, response to urgent clinical consultations can be facilitated by inexpensive communications[88]. As teleneurology activities support the expansion of neurological endeavours at academic medical centres in low-income and middle-income countries, centralized academic neurological providers in these countries ideally will use teleneurology to provide expertise and consultation to remote locations and non-specialists in their country[42]. Finally, remote assistance in the interpretation of neurodiagnostic technologies such as EEG and neuroimaging is increasingly feasible[84,89].

However, over-reliance on teleneurology could create pitfalls[50,88]. Teleneurology services, whether for health-care provision or medical education, are most effective when the external consultant is familiar with the local setting, including the resources available for care, sophistication of local health-care systems, cultural conditions or customs that affect health and local disease epidemiology[88]. As in telestroke, external advisers who are not familiar with local conditions or lack pre-existing relationships are poorly equipped to provide teleneurology support because the experts' lack of

Table 1 | **Randomized controlled trials of teleneurology for chronic care delivery**

Study	Condition	Sample size	Intervention	Country	Clinician	Patient location	Findings
Chua et al. (2001)[62]	General neurology	141	Video visits	UK	Neurologist	In clinic	In-clinic conference-style video visits were feasible. Video visits were not as cost effective as standard care
Phillips et al. (2001)[61]	Spinal cord injury	111	Video visits or telephone consultation	USA	Nurse	At home	Video visits yielded improved long-term health-related and quality of life outcomes. Hospital stays were reduced by over 50% at 1 year after discharge
Egner et al. (2003)[60]	Multiple sclerosis	111	Video visits or telephone consultation	USA	Therapist	At home	Video visits yielded favourable long-term quality of life outcomes at 2-year follow-up. Fatigue and depressive symptoms were reduced
Dallolio et al. (2008)[59]	Spinal cord injury	180	Video visits	Italy	Therapist	At home	Video visits were as effective as in-person rehabilitation. No difference in clinical complications was found at 6 months after discharge
Finlayson et al. (2011)[58]	Multiple sclerosis	190	Group-based telephone conference	USA	Therapist	At home	Group-based teleconferencing was effective in managing fatigue. Effect of fatigue symptoms was reduced at 6 months after discharge
Mackelprang et al. (2016)[57]	Spinal cord injury	168	Telephone counselling	USA	Counsellor	At home	Telephone counselling was as effective as in-person care. No difference in medical complications, health-care utilization or psychosocial outcomes were observed at 1 year after discharge
Müller et al. (2017)[54]	Nonacute headache	402	Video visits	Norway	Neurologist	In clinic	One-time telemedicine consultations were non-inferior to in-person consultations for nonacute headaches
Beck et al. (2017)[56]	Parkinson disease	195	Video visits	USA	Neurologist	At home	No difference in quality of life between in-person and virtual visits was observed, and patients preferred virtual visits with remote specialists to usual care with local physicians
Comans et al. (2017)[55]	Cerebral palsy	102	Web-based physical therapy programme	Australia	Physical therapist	At home	The programme was effective in improving upper limb function and was relatively cost effective. Video visits were preferred to usual in-person care

Published randomized controlled trials of teleneurology for chronic care delivery from 1992 to 2017. Owing to volume, trials with fewer than 100 participants were excluded. The trials covered many chronic conditions, ranging from headache to multiple sclerosis to Parkinson disease. Generally, they demonstrated both feasibility and acceptability for patients and clinicians.

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Table 2 | **Smartphone studies using sensors to assess neurological conditions**

Study	Condition	Sample size	Assessment	Country	Patient location	Findings
Mano et al. (2015)[101]	Parkinson disease	57	Smartphones measuring gait and posture	Japan	In clinic	Smartphone app and traditional measures both showed abnormal gait and posture in persons with Parkinson disease relative to healthy controls
Bot et al. (2016)[98]	Parkinson disease	14,684	Smartphone app with multiple sensors to evaluate disease symptoms	USA	Anywhere	Smartphone app can enrol participants nationally and assess multiple motor features of Parkinson disease
Lee et al. (2016)[99]	Parkinson disease	144	Validation of smartphone finger tapping as a bradykinesia metric	Korea	In clinic	Smartphone tapping generates comparable results to conventional methods of assessing motor dysfunction
Lee et al. (2016)[100]	Parkinson disease	103	Validation of smartphone app measuring motor function	Australia	In clinic and at home	Smartphone app showed significant correlation and satisfactory repeatability with a gold-standard clinical assessment
Barrantes et al. (2017)[102]	Parkinson disease and essential tremor	52	Smartphone accelerometer assessment of tremor kinetics	Spain	In clinic	Smartphone accelerometer recordings are clinically useful in distinguishing between conditions causing tremor
Vianello et al. (2017)[95]	General motor performance	133	Smartphones assessing motor function	Italy	In clinic	Smartphones can distinguish between normal and impaired neuromuscular performance
Lee et al. (2017)[96]	Parkinson disease	92	Smartphone motor assessment to evaluate sleep benefit	Australia	At home	Individuals with self-reported improvement in morning symptoms following sleep did not show commensurate motor improvements as measured by smartphone sensors
Rhea et al. (2017)[97]	Traumatic brain injury	59	Stepping in place task measuring motor function after low-level blast exposure	USA	At work	Navy personnel exposed to repetitive low-level blasts from heavy weapons fire showed neurocognitive and neuromotor decline in smartphone assessments

Published studies of smartphone applications that use the device's built-in sensors to assess neurological conditions from 1992 to 2017. Owing to volume, trials with fewer than 50 participants were excluded. Many of the studies focused on validating smartphone metrics against traditional in-person assessments.

regional knowledge and the health-care workers' lack of specialty knowledge make accurate communications challenging (for example, differential diagnosis of seizure varies substantially depending on the region of the world). Teleneurology cannot and should not replace in-country neurological services, and well-intended provision of some remote services might decrease political will and funding for the development of local services. However, when properly employed, teleneurology can help advance neurological services in low-income and middle-income countries, including through the use of mobile phones.

Emergence of mobile technologies

In addition to the use of teleneurology for provision of remote care, a second trend is emerging — the use of mobile technologies such as smartphones and wearable sensors. These tools have been developed only within the past few years, and their application to health and neurological disorders is even more recent[90], with few studies conducted using these technologies before 2015 (FIG. 1b).

The proliferation of smartphone ownership, improvement of mobile broadband coverage, decline in technological costs and increases in functionality, in combination with the substantial shortcomings in current metrics of the symptoms of neurological disorders, are all driving interest in these new tools[91]. For example, current measures of disorders such as AD rely on subjective, episodic, insensitive assessments (such as the cognitive subscale of the Alzheimer Disease Assessment Scale) that are exclusively conducted in clinic[92]. These limitations lead to incomplete clinical assessments of patients and prevent efficient evaluation of new therapies[93]. By contrast, new mobile technologies provide the opportunity to obtain objective, frequent (or even continuous) and sensitive assessments that can be performed in real-world environments and offer the potential of creating a so-called digital phenotype (that is, the expression of an individual's disease state through the lens of interactions with the digital environment)[94].

Smartphone technology has been applied to multiple neurological conditions for several purposes, including the improvement of measurement of the condition (such as tapping speed and tremor severity in individuals with PD)[95–102], education of patients and their families, provision of support services and enabling delivery of remote care[103,104] (TABLE 2). In the past few years, research has sought to validate assessments enabled by the sensors within smartphones (such as EEG measurements in people with epilepsy) against traditional rating scales or diagnostic assessments[84]. Future work will seek to use smartphone technology to measure outcomes that are largely impossible with current scales. For example, Global Positioning System (GPS) could be used to measure the 'lifespace' (that is, the geographic area in which an individual lives and conducts their activities) of individuals with PD, back pain

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or depression[105]. Other novel measures (for example, the number of words spoken or turns made by an individual) might also be enabled by these devices. Other investigations might use this technology to identify environmental risk factors or triggers for neurological diseases, as has been done for asthma[106].

Researchers have also begun to evaluate the ability of wearable sensors to provide objective measures of disease[84,107–117] (TABLE 3). Consumer devices (for example, fitness trackers such as Fitbit) are used by many people with neurological disorders[118] and have fuelled a 'quantified self' movement[119,120] in which individuals seek to obtain health insights through self-measurement of heart rate, movement, sleep patterns and EEG tracings. By contrast, research evaluations of trackers such as these are in the early stages, and most studies have assessed the wearable sensors only in a clinical setting, missing the opportunity to identify behaviours on the basis of real-world activities[110].

In the future, mobile technologies will be integrated with care. In cardiology, for example, pacemakers, implantable cardioverter–defibrillators and loop monitors enable passive monitoring of heart rhythms that can lead to rapid detection of abnormal rhythms and improved care[121,122]. Remote monitoring for chronic conditions, such as congestive heart failure, asthma and

Table 3 | **Wearable sensor studies to assess neurological conditions**

Study	Condition studied	Sample size	Assessment	Country	Patient location	Findings
Pasluosta et al. (2015)[113]	Parkinson disease	139	Postural assessment using wearable inertial sensors	Germany	In clinic	Wearable foot sensors can estimate postural instability in Parkinson disease
Pau et al. (2016)[111]	Multiple sclerosis	105	Gait assessment using wearable sensors	Italy	In clinic	Wearable sensors are useful for quantitatively assessing gait under realistic conditions in people with multiple sclerosis
Pérez-López et al. (2016)[112]	Parkinson disease	92	Motor assessments using an accelerometer	Spain	At home	A single belt-worn accelerometer can detect dyskinesias with >90% accuracy in persons with Parkinson disease
Silva de Lima et al. (2017)[117]	Parkinson disease	953	Long-term motor analysis using smartwatch sensor and accelerometer	Netherlands, USA and Canada	At home	Wearable sensors are feasible for collecting long-term data of daily motor activity in individuals with Parkinson disease
Schlachetzki et al. (2017)[116]	Parkinson disease	291	Gait assessment using wearable sensors	Germany	In clinic	Wearable sensors are useful for quantitatively assessing gait impairment in people with Parkinson disease
Jeon et al. (2017)[115]	Parkinson disease	85	Tremor severity scoring using wristwatch wearable sensor	Korea	In clinic	Machine-learning algorithms, combined with wearable sensor data, can score Parkinsonian tremors with >85% accuracy
Suppa et al. (2017)[114]	Parkinson disease	60	Gait assessment using wearable sensors	Italy	In clinic	A wireless wearable sensor system can detect freezing of gait in patients with Parkinson disease with >98% accuracy
McKenzie et al. (2017)[84]	Epilepsy	205	Abnormal electrical activity detection using wireless headband	Bhutan	In clinic	Wearable headbands are not as sensitive as traditional EEG but may be useful in extending low-cost EEG capabilities to resource-limited areas
Bonora et al. (2017)[107]	Parkinsonism	103	Postural assessment using inertial sensors	Italy	In clinic	Wearable sensors can distinguish between the ability of healthy controls and people with parkinsonism to adjust posture in response to balance shifts
Kegelmeyer et al. (2017)[108]	Huntington disease	77	Motor assessments using iPod or iPad sensors	USA	In clinic	Wearable iPod or iPad sensors are useful in assessing and rehabilitating irregularities in truncal movement in persons with Huntington disease
El-Gohary et al. (2017)[109]	Multiple sclerosis	73	Postural assessment using inertial sensors	USA	In clinic	Wearable sensors are useful for quantitatively assessing postural responses in persons with multiple sclerosis
Adams et al. (2017)[110]	Huntington disease, prodromal Huntington disease and Parkinson disease	56	Motor assessments using wearable sensors	USA	In clinic and at home	Wearable sensor use is feasible and well received among individuals with movement disorders and can distinguish activity profiles of those with and without disease

Published studies of wearable sensors to assess neurological conditions from 1992 to 2017. Owing to volume, trials with fewer than 50 participants were excluded. The studies were conducted mostly in clinic. Wearable sensor systems ranged from commercial (for example, Fitbit) to proprietary, and many focused on validation of wearable sensor data against traditional in-person assessments.

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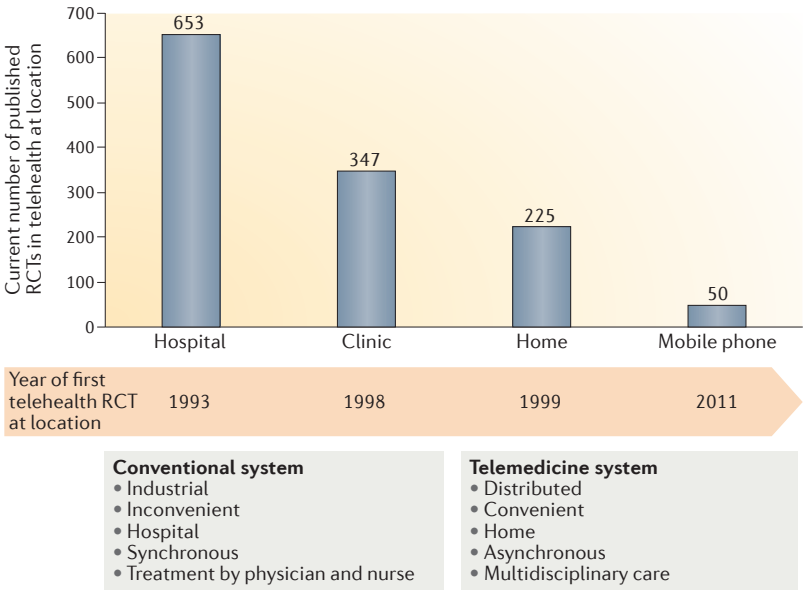

Figure 2 | **Migration of telehealth.** The migration of telehealth mirrors the trends observed in other industries, such as banking and retail, with services moving from institutions (banks and hospitals) to local centres (shopping mall ATMs and clinics) to the home and mobile devices. ATM, automated teller machine; RCT, randomized controlled trial.

diabetes mellitus, is increasingly standard practice[123], with care delivered either remotely by audio or video calls, or in person, often by visiting nurses.

The same model is now emerging for epilepsy[124]. The past year has seen the development of a smartphone app combined with a smartwatch that has the potential to detect seizures[125], quantify them and notify a patient's clinical team. In the future, such tools could alert emergency services on the basis of seizure duration or changes in vital signs and could help to combat sudden unexpected death in epilepsy[126]. Current technologies can also integrate the remote assessment of sleep with clinical care, without the need for expensive, inpatient polysomnography. Future technologies will provide even greater insights, currently inaccessible in traditional clinical settings, into neurological conditions. Innovations will focus on novel ways of measuring clinically meaningful outcomes (for example, time alone and time with others as a measure of socialization). A major challenge will be to separate the clinically meaningful signals from the abundant noise that these sensors will generate. Initially, large amounts of labour will be required to filter this noise (for example, within accelerometry tracings) and to develop algorithms that accurately identify important clinical signals (such as seizures).

Future trends

Several mutually reinforcing trends will shape the future of neurological care. The first is the expansion and migration of care from traditional locations such as hospitals and clinics to homes and mobile devices (FIG. 2). This migration mirrors the same trends that are occurring in telestroke and in other industries outside of medicine, such as banking and retail. Initial teleneurology applications were focused on the delivery of remote neurological care to patients in hospitals. Now, many applications and programmes — such as the Ontario Telemedicine Network in Canada[127] and the US Department of Veterans Affairs[128–130] — provide remote care in satellite clinics close to where patients live. These satellite clinic locations have also multiplied and now include kiosks or stations in airports[131,132], pharmacies[19] and retirement communities[133]. Care programmes are also beginning to emerge that provide care to patients directly in their homes[55–61,128,134]. Such home care is convenient and patient-centred but requires patients or their friends and families to have access to and familiarity with Internet-enabled technologies[56], which is increasingly becoming the norm[135]. Moreover, such care requires minimal investment in sites and labour (such as clinic buildings and the staff required to manage them) and — as with banking and retail — can be offered 24 hours per day, 7 days per week to large populations, including those with limited access to neurological care.

Even telestroke care is moving close to the home. In Germany[136,137] and the USA[138], ambulance-based mobile stroke units are delivering acute stroke care — including evaluation by a remote neurologist, a CT scan, blood work and tissue plasminogen activator administration. Telestroke services will eventually migrate to smartphones[42]. In a 2016 study, four neurologists in India were equipped with smartphones to enable remote evaluation and transmission of CT scans for patients experiencing possible strokes in a population of nearly 7 million people[42]. Future models could enable patients to be evaluated remotely on their own smartphones, perhaps triggered by a call to emergency medical services. Such smartphone applications are already emerging in low-income and middle-income countries[139] and could provide acute neurological care in global humanitarian crises[88].

The evolution of teleneurology is also driven by a need to deliver care in low-cost settings[140]. Industrializing nations such as China (which spends US$731 per person on health care)[141] and India ($267 per person)[142] will build a few major medical centres but will use technology to deliver health care inexpensively to the millions of citizens who live outside of major cities. The dominant means for this health delivery will be smartphones[143]. By 2020, 70% of the world's population is projected to have a smartphone[144] (FIG. 3), and these smartphones will deliver care where patients, as opposed to medical centres, are located. High-income countries, which are currently confronted with rising health-care expenditures, will also seek care models that do not require expensive buildings, parking lots, waiting rooms, clinic spaces and labour[18].

An additional factor driving the adoption of teleneurology is that consumers, especially those paying for health care, will demand convenience. Current health care is inconvenient[9]; long waiting times, congested parking facilities, outdated waiting rooms and rushed clinical encounters are frequently the norm[145,146]. Just as

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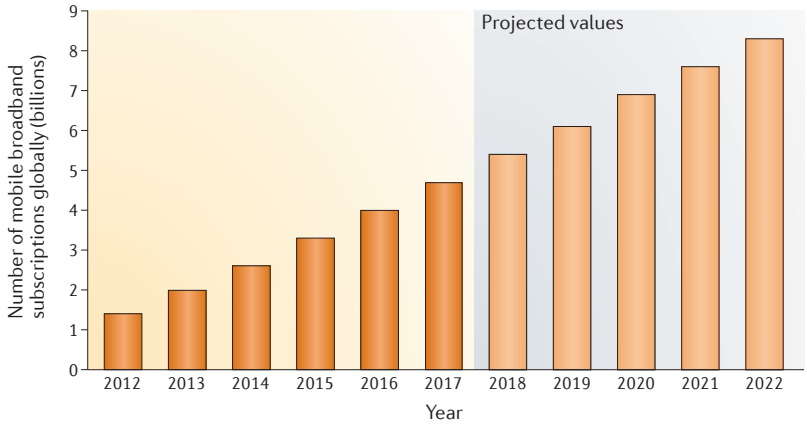

Figure 3 | **Number of mobile broadband subscriptions, globally.** A graph of smartphone ownership (measured by number of global broadband subscriptions) from 2012 to 2022. Smartphone ownership rates have steadily increased; by 2020, 70% of the world's population is projected to own a smartphone[193].

consumers have come to expect on-demand shopping, travel and media services, so too will they expect rapid health solutions such as on-demand urgent care[147] and even house calls[148].

Another future trend is the supplementation of current synchronous care models with asynchronous communications[20]. Traditional clinical encounters are between a patient and a clinician who are co-located in space and time; teleneurology enables patients and neurologists to be separated in this respect. Electronic health record portals permit and even encourage patients to communicate with clinicians asynchronously[18]. In an integrated care delivery system in the USA, the number of e-mail, phone and video encounters between patients and clinicians now exceeds the number of in-person clinic visits[149]. Remote monitoring from sensors will enable clinicians to track patients' health and intervene without an appointment or schedule one when data, rather than convention, suggest that it would be valuable.

The rise of teleneurology will also enable a greater variety of clinicians to play a part in patient care[55,57–60]. In addition to traditional clinicians (for example, neurologists, psychologists and nurses), allied health professionals (such as pharmacists, nutritionists, speech therapists[150] and social workers)[151] and new kinds of health providers (such as exercise coaches, music therapists and those who design and facilitate the operation of support groups) will provide care and services to individuals with chronic neurological conditions. In many cases, the care will involve groups of patients, and technology will enable 'one-to-many' care models that enable one clinician to connect simultaneously to multiple patients[152–154] or many patients to connect to one another and provide peer-to-peer support[155]. For example, ParkinsonNet[156], an integrated care network in the Netherlands, has developed ParkinsonTV, which assembles neurologists, experts such as therapists and dieticians, and patients to provide live educational programming to those affected by PD[157]. Viewers can pose questions in real time, and those that miss an 'episode' can watch later, as tens of thousands of people have.

Finally, all these trends point toward the evolution of a distributed and personalized model of care delivery. Rather than assembling neurologists and patients in the same location and providing a uniform service to all (for example, a 15-minute clinical appointment), individuals might increasingly receive care from a geographically dispersed network of clinicians. ParkinsonNet is an early example of such a network, comprising thousands of allied health professionals in the Netherlands, and it is now being exported to other European countries and to the USA[157]. These networks will include multiple clinicians, remote monitoring and care delivery for patients through mobile devices and will enable more frequent care than is currently available through conventional health-care systems. In the future, an annual 30-minute follow-up visit with a neurologist could be deconstructed into multiple shorter consultations with a diverse set of clinicians, giving patients the advantages of both a wider range of expertise and more frequent follow-up visits.

Timing of the future of teleneurology

The timing of the emergence of teleneurology is uncertain. However, technological change is not linear but exponential; as adoption occurs, more resources are allocated[158]. Teleneurology for chronic conditions is still at an early stage, but there are indications of increasing adoption of these systems. For example, in the Ontario Telemedicine Network, the number of outpatient visits from 2009 to 2014 increased fivefold (FIG. 4a). Although initial applications of teleneurology were primarily in rural areas, adoption of such systems has now become more rapid in urban areas, which could reflect a desire for more convenient care. In addition, the US Department of Veterans Affairs has experienced an exponential increase in the adoption of telehealth at many of its centres, including a 25-fold increase in telemedicine visit volume between 2005 and 2013 at one Vermont location[159]. Several US medical centres have indicated plans to adopt telehealth rapidly, including a plan in the NewYork-Presbyterian Regional Hospital Network for 20% of clinic visits to be conducted remotely by the end of 2018 (REF. 160). Furthermore, the Mayo Clinic has stated a goal of having meaningful interaction with 200 million individuals by 2020 (REF. 161), which almost certainly requires broad-scale adoption of telehealth to achieve a global reach.

As disruptive technologies are developed, adoption usually begins at low levels and increases exponentially[162]. On the basis of industry forecasts[163–166], the adoption of teleneurology in the USA could also follow a similar pattern (FIG. 4b). However, health care has many factors that might slow this trend[167].

Barriers and limitations

Teleneurology faces a number of major technological, political, clinical and social barriers. Although Internet use approaches or exceeds 90% among individuals in high-income countries[168], global Internet access is just over 50% and is less than one-third in Africa[169]. Internet access is highly correlated with per-capita income but is

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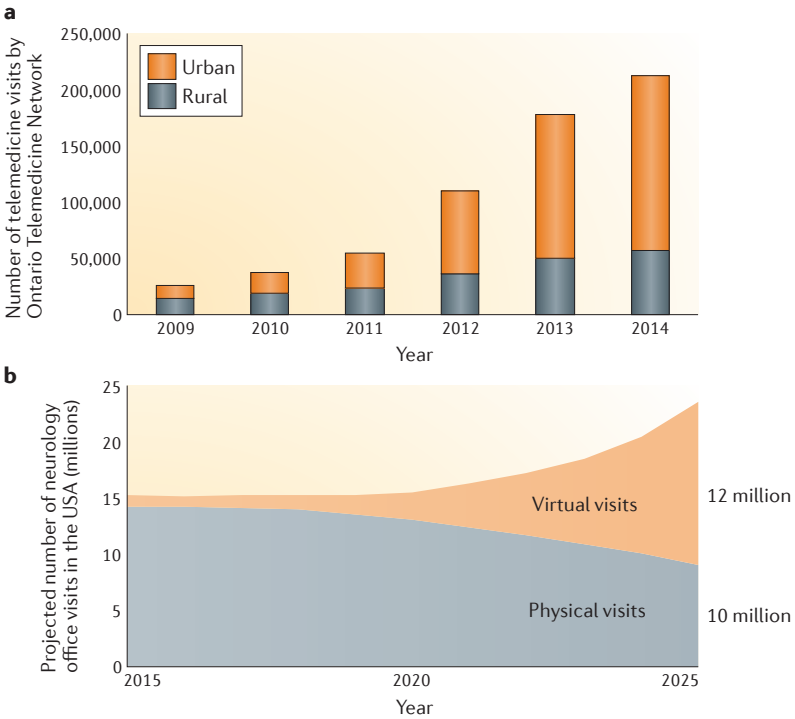

Figure 4 | **Rise in number of telemedicine visits. a** | A graph of the number of telemedicine visits in an integrated care network (the Ontario Telemedicine Network in Canada) between 2009 and 2014. This growth exemplifies the rapid adoption of telehealth. Although initial telehealth visits were mostly in rural areas (grey), the number of urban visits (orange) has increased exponentially and now dominates. Excludes those reported as 'missing location', which accounted for <1% of all visits[194]. **b** | A graph estimating the number of US virtual and conventional physical neurology office visits from 2015 to 2025 (REFS 195,196). Virtual visits could outnumber traditional in-clinic visits by 2025.

growing in virtually all parts of the world[168]. Currently, two-way video conferencing is not widely available in low-income countries, and telehealth applications in these locations are limited to traditional phone calls or store-and-forward applications, such as review of pathology or dermatology cases[170]. Improvement of Internet access, development of new technologies that bridge last-mile connectivity (such as the provision of Internet access in town centres or equivalent locations in communities whose homes generally lack access), especially in rural areas[171], and increases to cell and smartphone ownership[172] are all likely to benefit future telehealth applications.

Policy-related obstacles, especially a lack of health-care reimbursement, also slow the adoption of teleneurology. The current over-reliance on in-person care reflects existing payment models that reward institution-based care and penalize patient-centred care. In Asia[173], Europe[174] and North America, coverage of teleneurology for chronic neurological conditions is slowly emerging. For example, in the USA, 29 of 50 states mandate that private insurers cover telehealth services, and 48 of 50 states have some telehealth coverage for those with low income[175]. However, Medicare (the US program that insures those over 65 years of age) covers telehealth only in "health professional shortage areas" and is changing slowly; the US Congress passed the first major telehealth reimbursement legislation in more than a decade as part of a 2018 budget agreement[176]. By contrast, in Canada, where health-care coverage includes a supplemental technology fee, adoption of telehealth has been rapid[127]. Countries (such as Canada), populations (such as clients of the US Department of Veteran Affairs[129]) with a single-payer system or programmes that integrate finance and delivery of health care (such as Kaiser Permanente[149]) have adopted telehealth extensively as a means to increase access often to low-cost care.

Many insurers also seek cost-effectiveness studies before extending coverage. For telestroke, long-term financial benefit offsets upfront investments, and insurance coverage is now cost neutral to insurers[177]. Importantly, these analyses frequently exclude the perspective of the patient, to whom most of the economic benefit accrues[178]. The expenditures associated with travel and waiting can equal the costs of a clinical encounter[80], but these expenditures do not affect insurers or clinicians, which frequently results in inertia from these groups with regards to changing current health-care systems.

In addition to reimbursement challenges, antiquated and changing medical credentialing and licensure requirements between different countries and across state lines in the USA hinder adoption[179,180]. The result is that telehealth applications across national borders are often only between clinicians, as opposed to between clinicians and patients.

Teleneurology also threatens current care models, including the relationship between local clinicians and patients. For example, similar disruptive models for travel and retail have threatened certain existing groups in these industries (for example, travel agencies, book stores and shopping malls). Teleneurology can do the same by 'disintermediating', or bypassing, local clinicians in the care of patients with neurological disorders. In some cases, telestroke has spared local neurologists, many of whom were initially content to have others be on call for stroke emergencies. However, as is the case for many disruptive technologies, the scope of services could increase (for instance, introduction of daytime stroke coverage and inpatient consultations) and threaten local clinicians. On the other hand, teleneurology can increase the capacity of local clinicians — as it has done for many emergency room physicians — through face-to-face meetings, educational sessions and ongoing joint care of patients with remote specialists. For example, Project ECHO uses remote experts to enable local clinicians to care for a broader set of patients. Such models are crucial for increasing the capabilities of local clinicians, especially in resource-limited countries. Forging these relationships is time intensive and labour intensive but crucial to realizing the potential of teleneurology.

However, the biggest barrier for teleneurology is not technological, political, financial or clinical, but social. The digital divide — the differential access to Internet and related technologies due to social and economic factors — is the greatest obstacle to overcome[181]. The fundamental aim of teleneurology is to increase access

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Box 1 | **Limitations of this Review**

This Review has its own set of limitations, including its perspective, scope and sources. Because the article was written by neurologists from the USA, it could have missed or underemphasized key issues that are affecting the adoption and development of teleneurology in major regions of the world. Other than telestroke, this paper focuses on chronic neurological conditions and largely does not discuss other models that are developing to care for individuals with acute neurological conditions or neurological conditions that require inpatient care[187–189]. The Review also identifies trends affecting neurological care but does so from the perspective of technology-enabled models. Many other care models, including palliative care[190], community-based health-care providers[191] and in-person house calls[192], will influence the future of care delivery. Finally, the evidence base for this paper was largely collected by literature review. In some cases, key study aspects (for example, location of patients and clinicians providing care) were difficult to ascertain. In addition, the studies identified probably downplay contributions from many low-income nations, and like most clinical activities, teleneurology efforts are often unpublished and thus understated.

to care, but those with the most need often have the least access to or familiarity with the enabling technology. For example, individuals who are elderly, have chronic medical conditions, have low incomes or live in rural areas are all less likely to have broadband Internet access[135,182]. Although mobile broadband costs have decreased by 60% in low-income countries since 2013, only 20% of the population in these areas currently has access compared with 50% in middle-income countries and almost 100% in high-income countries[183]. Although teleneurology addresses geographic barriers[130], studies of teleneurology (such as clinical trials[184]) often have few participants from ethnic minorities in the USA and skew toward highly educated populations[134]. The result could be that teleneurology, rather than reducing social and economic barriers to care (as it has done in telestroke[185]), magnifies disparities by providing preferential access to those who are already best served. In the short term, satellite teleneurology clinics in underserved regions might be necessary to increase access to care for those who need it the most. In the long term, education, improved broadband access and support of underserved populations will be required to ensure equitable distribution of care.

In addition, this Review has its own set of limitations to be considered. These are discussed in BOX 1.

Conclusions

Neurological disorders are now the leading source of disability globally[44,45]. Moreover, the burden of chronic disorders, especially neurodegenerative conditions such as AD and PD, will shift from West to East and is predicted to double worldwide over the next 25 years[186]. Access to neurological care is already scarce, and its supply and distribution are unlikely to match its demand.

Consequently, new care models are needed, and teleneurology provides a potentially powerful solution via ubiquitous and inexpensive technology. In less than two decades, telestroke has increased access to effective acute stroke treatment for millions of people around the world. Teleneurology can do the same for tens if not hundreds of millions of people with chronic neurological disorders. Delays, whether due to political, financial, clinical or social barriers or due to simple inertia, carry immense costs. Today, too many people are experiencing seizures, pain, impaired mobility and premature mortality from treatable neurological conditions. With therapeutic advances, the ranks of these treatable conditions will grow, but treatments will be limited to those who can access care.

To address this challenge, the substantial shortcomings in current care must be recognized, novel care models that increase access and leverage smartphone technology must be embraced, and barriers, especially social barriers, to greater use of technology must be addressed. With these changes, we are positioned — for the first time in history — to provide neurological care to almost anyone, anywhere.

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Author contributions
All authors researched data for the Review, made substantial contributions to the discussion of the content of the article and reviewed and edited the manuscript before submission. E.R.D., G.L.B. and L.H.S. wrote the article.

Competing interests
E.R.D. is a member of the medical advisory board and owns stock options in Grand Rounds, an online second-opinion service, is a consultant to MC10, a wearable sensor company, and has research grants related to telehealth from AbbVie, the Burroughs Wellcome Fund, the Greater Rochester Health Foundation, the US NIH, the Patient-Centered Outcomes Research Institute and the Safra Foundation. L.H.S. is a consultant to and owns stock options in LifeImage, a teleradiology company, and is the teleneurology consultant to several network research grants from the US NIH and the Patient-Centered Outcomes Research Institute. G.L.B., A.M.G., and M.R.H. have no competing interests to declare.

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Review criteria
The authors searched PubMed for articles published through December 2017 unless otherwise indicated. Search terms were "neurology" and the names of 12 common neurological disorders (autism, cerebral palsy, Tourette syndrome, migraine, epilepsy, multiple sclerosis, stroke, traumatic brain injury, spinal cord injury, Alzheimer disease, Parkinson disease and amyotrophic lateral sclerosis). Depending on the search, additional search terms were "telehealth", "smartphones" and "wearable sensors", and PubMed's "randomized controlled trial" filter was applied. The authors supplemented searches on the basis of literature reviews and articles known to the authors. PubMed search terms for the tables and figures are summarized here. Figure 1a: (neurology or related disorders above) AND (telehealth) NOT (stroke). Figure 1b: (neurology and related disorders above) AND (smartphone); (neurology and related disorders above) AND (wearable sensors). Figure 2: (telehealth) AND (healthcare delivery) AND ((hospital) OR (clinic) OR ((home) NOT (home monitoring)) OR (smartphone)). Table 1: (neurology or related disorders above) AND (telehealth) NOT (stroke) FILTER (Randomized Controlled Trial). Table 2: (neurology and related disorders above) AND (smartphone) NOT (stroke). Table 3: (neurology and related disorders above) AND (wearable sensors) NOT (stroke).

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