The delivery of medical care through telecommunication has been available in one form or another for ≈100 years. In the early 1900s, people living in remote areas of Australia used 2-way radios (powered by dynamos and bicycle pedals) to communicate with the Australian Royal Flying Doctor Service. The first direct reference to telemedicine in the literature was in the 1950s, with the transmission of radiological images by telephone in Philadelphia, closely followed by the teleradiology system established in Montreal, Canada.\(^1\) Telemedicine by video communication was first implemented by the University of Nebraska in the 1960s to allow clinicians to service remote populations.\(^2\) Jumping forward to the 21st century, there are now ≥55 telestroke programs in 27 states of the United States that deliver stroke services to ≥350 spoke hospitals.\(^3\)

To justify the use of telestroke, there is a need for evidence of benefit. However, evaluating the outcomes of a telestroke program is complex because clinical outcomes from treating patients with acute stroke and wider health system and financial metrics need to be captured. The purpose of this review is to provide an overview of the various outcomes of stroke telemedicine and to outline the new paradigms evolving for systems of care, research, and education, as well as financial considerations.

**Background**

Stroke telemedicine (or telestroke) is the practice of clinical stroke care via telecommunication and came into its own with the era of stroke thrombolysis in the late 1990s. A key driver was to ensure better equity for patients in accessing this time-critical therapy in metropolitan and rural hospitals. Our knowledge base on the benefits of stroke thrombolysis continues to develop. The totality of evidence through pooled data analysis indicates that the therapeutic benefit of recombinant tissue-type plasminogen activator (tPA) is time dependent and is greatest when given early after stroke onset but with diminishing efficacy ≥4.5 hours.\(^4\) When used appropriately, tPA is one of the most effective treatments for acute ischemic stroke, with a number needed-to-treat ranging from 4.5 (if used within 3 hours) to 14 (if used within 4.5 hours).\(^5\) This benefit occurs despite an increase in the number of early symptomatic intracranial hemorrhages and early deaths. Data from a large US stroke registry of 58,353 tPA-treated patients was used to show the temporal effect of delays in tPA treatment.\(^6\) In this analysis, thrombolytic treatment was associated with greater rates of independent ambulation at discharge and greater likelihood of discharge to home. Importantly, it was revealed that adverse events were also time dependent, with fewer occurrences of symptomatic intracranial hemorrhage and deaths with earlier stroke onset-to-treatment time.\(^7\) Recent data from the International Stroke Trial 3 (IST3) are consistent with previous analyses, indicating benefits for patients aged ≥80 years, and improvements in functional outcome and health-related quality of life for ≥18 months after stroke.\(^8\) In many hospitals, improvements in acute stroke systems of care have reduced the ideal door-to-needle time of a Golden-Hour down to 20 minutes.\(^6,7\) Moreover, recent simulation modeling in Australia has revealed that for every minute a patient is treated earlier with tPA, their disability may be reduced by ≈1.5 days (range, 0.5–2.1).\(^8\)

Despite the growing body of evidence for tPA, even countries with advanced healthcare systems have a geographical disparity in the delivery of stroke thrombolysis. For example, in the United States, only 55% of Americans have access to primary stroke centers within 60-minute drive time, and nearly half of all hospitals have fewer than 100 beds most with no staff neurologists.\(^9\) Accordingly, patients with acute ischemic stroke presenting to rural emergency departments are 10× less likely to receive tPA than those presenting to urban primary stroke centers.\(^9\)

Public awareness campaigns, and advances in telecommunication technology and network bandwidth, have helped propel telestroke as a mainstream consideration for patients with acute stroke. For rural hospitals, transferring patients to a tertiary hub is costly, inconvenient, stressful for patients, family and staff, and at times medically unsafe. Telestroke can enable...
rural hospitals to deliver tPA onsite instead of transferring the patients to specialized stroke centers.10–12 The newfound ability to deliver onsite stroke thrombolysis may motivate many hospitals to implement a drip and keep organized systems of stroke care, thus moving from a drip and ship model. Indeed, active teleneurology networks have achieved a 60% to 70% patient retention at local hospitals, with significant cost savings and improved financial viability of these rural health services.13,14

The ground is fertile for stroke telemedicine to flourish and to improve the quality of care for patients with stroke, no matter the geographic location. The advent of telestroke 2.0 has expanded the mobile capabilities of stroke care to computer tablets, laptops, and smart phones.15 At a hospital level, the consultation is undertaken via a mobile computer cart or by remotely driven robot.14,16,17 At a software level, the delivery of acute stroke care by telemedicine has also now evolved to become a more user-friendly experience. Advanced stroke telemedicine applications are unified in that they can deliver audiovisual, Picture Archiving and Communication Systems (PACS) imaging, and clinical notes within a single software program.16,18,19

Clinical Processes of Care
Clinical processes and decision making for stroke thrombolysis in the emergency department can be reliably performed by telemedicine. Typically, the clinical assessment of stroke is undertaken using the National Institutes of Health Stroke Scale (NIHSS), a reliable and reproducible measure of neurological disability in stroke. Importantly, this can be done by telemedicine, with little additional time delay and with an inter-rater reliability, showing a strong correlation between NIHSS performed at the bedside and at a remote location (r=0.9552).20–22 The NIHSS clinical assessment is robust across different locations and technologies, including desktop computer, laptop, and even a prehospital clinical assessment using video cell phone.22,23 Moreover, the results are consistent even when the examination was performed by an inexperienced telemedicine examiner and between local and remote non-neurologists.24,25 The 2013 American Stroke Association (ASA) policy statement on Interactions Within Stroke Systems of Care recommends the use of telemedicine for NIHSS assessment of patients with stroke, with the results comparable with those of inpatient assessment (class I recommendation; level of evidence A).26

The evaluation of acute stroke brain imaging is fundamental to proceeding with stroke thrombolysis. Multimodal brain imaging (eg, computed tomographic [CT] perfusion and CT angiography) is increasingly influencing clinical decision making, but the DICOM image files generated are large and require file compression algorithms and high-speed broadband capacity. Efficient PACS teleradiology systems are a critical component within any telestroke system of care.11,26 High levels of agreement in the teleradiology review of acute stroke brain imaging can be achieved. A study undertaken within a stroke telemedicine network in Arizona demonstrated an overall excellent agreement (91%) about the presence or absence of CT contraindications to thrombolysis between hub and spoke neuroradiologists and neurologists.27 In a review of brain imaging of ≥500 patients by stroke specialists using telemedicine, only 1.7% of scans had clinically relevant discrepant findings when read by 2 neuroradiologists, demonstrating that misreading of CT scans in well-managed stroke teleradiology systems is uncommon.28 In keeping with this evidence, the recent 2013 ASA guidelines endorse that teleradiology systems are recommended for timely review of brain CT and MRI scans in patients with suspected acute stroke (class I; level of evidence B).11

Clinical Outcomes
The most important outcome is whether telemedicine has enabled clinicians to make the right treatment decision efficiently, and whether the quality of care and longer term outcomes of stroke have improved. It has been demonstrated that stroke telemedicine can increase rates of stroke thrombolysis in smaller community or rural hospitals with reduced time to treatment. The overall rate of stroke thrombolysis in the United States is <5%, a figure that is consistent internationally. However, hospitals using stroke telemedicine typically report tPA rates of ≥15% (of all strokes), with rates ≥50% in eligible patients with acute ischemic stroke.17,20–31 In Helsinki, Finland, a telestroke network of 5 community hospitals treated 61 of 106 (58%) patients with acute stroke and tPA when compared with 985 patients treated with thrombolysis at the university teaching hospital.29 When compared with patients treated with thrombolysis at the University Hospital, there was no significant difference in the 3-month outcomes of community hospital patients treated by teleconsultation with similar functional outcomes (modified Rankin Scale, 0–2; 58.1% versus 49.1%, respectively), mortality (10.2% versus 11.5%), and symptomatic intracranial hemorrhage (9.4% versus 6.7%). The authors concluded that teleconsultation for stroke thrombolysis was feasible and safe because the outcomes were comparable with an experienced stroke center. Furthermore, the use of telestroke resulted in a 2- to 3-fold increase in the use of thrombolysis in the smaller community hospitals.29

The Telemedic Pilot Project for Integrative Stroke Care network in Bavaria, Germany, undertook a nonrandomized open intervention study to compare 5 hospitals with tertiary level academic telemedicine network support and 5 matched community hospitals without telemedicine network support.32 More than 3000 patients with stroke admitted within a 2-year period were included in the final analysis. Significantly fewer patients treated in telestroke network hospitals than in control hospitals had a poor outcome (44% versus 54%) after 3 months. All indicators related to the quality of acute stroke care (eg, diagnostic procedures, and allied health assessments) were more commonly met in the network than in the control hospitals. In multivariable regression analysis, treatment in network hospitals independently reduced the probability of a poor outcome (odds ratio, 0.62; 95% confidence interval, 0.52–0.74; P<0.0001).32 The benefit in favor of treatment in hospitals supported by a stroke telemedicine network was sustained, with a significantly lower proportion of patients treated in Telemedic Pilot Project for Integrative Stroke Care hospitals having outcomes of death and dependency after 12
and 30 months of follow-up.\textsuperscript{33} Moreover, the Telemedic Pilot Project for Integrative Stroke Care group demonstrated the safety of thrombolysis via telestroke with in-hospital mortality and symptomatic intracranial hemorrhage occurring in only 10.4% and 8.5% of patients, respectively.\textsuperscript{14}

The California-based Stroke Team Remote Evaluation Using a Digital Observation Camera (STRoKE DOC) trial was designed to assess the efficacy of stroke telemedicine for acute decision making.\textsuperscript{38} In this randomized trial involving 222 patients with acute stroke, telestroke decision making was superior to consultation by telephone for administration of tPA. Correct treatment decisions were made more often in the telemedicine group than in the telephone consultation group (98% versus 82%; odds ratio, 10.9; 95% confidence interval, 2.7–44.6). The 90-day clinical outcomes did not vary between the groups, but the study was underpowered to detect differences in functional outcomes. The trial reported a high tPA using rate for both modalities at 25% overall (28% telestroke and 23% telephone).\textsuperscript{39} There was no difference in the safety of telemedicine and telephone-guided tPA assessments with regard to post-thrombolytic intracranial hemorrhage rate (7% versus 8%; \textit{P}=1.0). The tPA mortality was not significantly different after adjusting for baseline NIHSS score severity.\textsuperscript{35} A subsequent pooled analysis of data from a multisite telestroke network in California and Arizona, which included 54 patients from Arizona, randomly assigned to each treatment group, reinforced the finding of superiority of telestroke over telephone consultation in clinical decision making.\textsuperscript{9}

### Policies, Guidelines, and Resource Use

It is important to have appropriate policies and guidelines to enhance successful implementation of telestroke networks and support its efficient use.\textsuperscript{11,26} The ASA guidelines recognize the importance of stroke telemedicine to improve access to tPA, stating that: “a stroke specialist, using high-quality video teleconferencing, is able to provide a medical opinion in favor of, or against, the use of intravenous tPA in patients with suspected acute ischemic stroke when onsite stroke expertise is not immediately available (class I recommendation, level of evidence B).”\textsuperscript{36} ASA guidelines have also addressed the importance of stroke telemedicine to improve access and support its efficient use.\textsuperscript{11,26} The ideal scenario is that only appropriate patients are transferred to hub hospitals and other patients are kept in the spoke hospitals, thereby meeting a definition of quality by the Agency of Health Research and Quality in the United States: “doing the right thing, at the right time, in the right way, for the right person.”\textsuperscript{39} The benefits of the telestroke unit concept need to be balanced against the clinical limitations of stroke telemedicine (eg, conducting a complete neurological examination, staff and patient uncertainty with the technology, or conducting difficult discussions such as end-of-life decisions).

### Stroke Systems of Care

Beyond hyperacute treatments, such as tPA or endovascular therapies, patients with acute stroke benefit from organized care in a stroke unit. Monitoring of patients and provision of a multidisciplinary service with specialized nurses, speech therapists, occupational therapists, and physiotherapists is feasible in most hospitals. This can be supported with daily hospital rounds performed by neurologists via mobile telemedicine workstations. At small hospitals, some of this care could be delivered by remote nurse practitioners, under the direction of a stroke specialist.\textsuperscript{14}

At a more comprehensive level, a fully fledged telesystem of stroke care can be implemented, even commencing in the prehospital environment.\textsuperscript{26,37} Telemedicine can enable remote specialists to become virtually present to supervise stroke care throughout the hospital stay of a patient, even including telerehabilitation systems. This approach can be combined with digital transmission of patients vital-observations data, thus creating a virtual telestroke unit. The key elements of evidence-based stroke unit care, such as monitoring and treating the occurrence of raised temperature, abnormal blood glucose levels, and dysphagia status, can be delivered.\textsuperscript{38} The ideal scenario is that only appropriate patients are transferred to hub hospitals and other patients are kept in the spoke hospitals, thereby meeting a definition of quality by the Agency of Health Research and Quality in the United States: “doing the right thing, at the right time, in the right way, for the right person.”\textsuperscript{39} The benefits of the telestroke unit concept need to be balanced against the clinical limitations of stroke telemedicine (eg, conducting a complete neurological examination, staff and patient uncertainty with the technology, or conducting difficult discussions such as end-of-life decisions).

### Education and Research

Underpinning the evidence-based stroke treatments on offer to large and small communities through telemedicine is the ongoing need for education and research. Stroke is a complex and heterogeneous condition. Telestroke provides an important opportunity for stroke experts to deliver education about stroke mimics, diagnostic workup, and the rationale for a particular course of stroke management to spoke-based clinicians. Over time, this knowledge transfer may result in spoke hospital staff improving their skills and experience in stroke care and assuming greater autonomy for treatment decisions.

The evidence base for stroke care comes from research, and telemedicine can facilitate greater participation in research by providing infrastructure to recruit patients into clinical trials.\textsuperscript{40} Telemedicine can be used to screen patients, and with the assistance of local staff telerecruitment can take place. That is information about a clinical study can be discussed with the patient (or family/carers), consent undertaken (possibly by e-signature), before randomization.\textsuperscript{40} Trial participants may remain remotely located in collaborating spoke hospitals with follow-up also by telemedicine consultation.

In a climate where it is increasingly difficult to recruit patients into clinical research, this approach may ensure that sample sizes for stroke clinical trials are met within study timeframes.\textsuperscript{14,40}
Financial Considerations and Cost-Effectiveness

Finally, although telestroke networks have become widespread and represent an expanding model of stroke care, significant upfront costs are needed. An important consideration for any new service is cost-effectiveness. That is, are the costs of providing a telehealth service worthwhile for the additional health benefits gained? Another important aspect is whether stroke telemedicine can deliver a positive financial outcome for the health system through fewer patient transfers or admissions to nursing homes.

In general, there is mixed evidence on whether telehealth services provide value over other forms of delivering face-to-face services. Economic evaluation studies undertaken in the area of acute stroke care and telestroke are limited. \(^\text{13}\) Overall, telestroke networks seem to be cost-effective from a long-term, societal perspective. A cost-effectiveness analysis was conducted to compare hub and spoke telestroke networks with usual care (emergency physicians without telestroke consultations). \(^\text{41}\) Using a decision-analytic model, when compared with usual care, the telestroke networks provided an incremental cost-effectiveness ratio of $108,363/quality-adjusted life year gained for a 90-day horizon and $244,49/quality-adjusted life year gained for a lifetime horizon. The differences in results from the 2 time horizons illustrate the effect of the initial costs of establishing a stroke telemedicine service, which are balanced over the longer term by the reduced need for rehabilitation and advanced nursing care when there is increased use of tPA.

In another study, data from 2 US telestroke networks were used to develop a decision-analytic model to compare costs and effectiveness with and without a telestroke network for a 5-year time horizon. \(^\text{42}\) Differences in rates of teleconsultations, intravenous thrombolysis, endovascular stroke therapies, and spoke-to-hub transfers were modeled. It was demonstrated that a telestroke system results in more intravenous and intra-arterial thrombolysis, more patients discharged home independently, and, despite upfront and maintenance expenses, greater cost savings for the entire network. \(^\text{42}\) Similarly, the incremental cost-effectiveness ratio for a hub and spoke telestroke system in a Danish study was $50,000/quality-adjusted life year gained after 1 year, indicating the borderline cost-effectiveness. However, telestroke became the better system of care from both a cost (cheaper) and quality (more effective) perspective in as little as 2 years, with cost savings occurring over time. \(^\text{43}\)

Further economic evaluations of telestroke are warranted in different countries because models of care will vary. In addition, patient- and service-level data should be used with a sufficient time horizon to account for the benefits of tPA in reducing disability.

Conclusions

Technological advances of the 21st century are rapidly changing the landscape of public healthcare. Stroke telemedicine networks are flourishing and allow acute stroke therapies to be accessible to all, regardless of geographical location. The outcomes of telestroke are many and varied, but importantly they are reproducible and seem financially sustainable. For many years, stroke was viewed as an orphan disease, with limited capacity for meaningful treatment. With improvements in technologies and systems of care, telemedicine can encompass all aspects of care from prehospital to stroke rehabilitation, so we are now truly on the cusp of a telestroke revolution. Establishing appropriate infrastructure, including policies, standards, and sustainable financial reimbursement models, will ensure the success of progress in this field.

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References


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Christopher F. Bladin and Dominique A. Cadilhac

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