Point-of-Care Ultrasound in Neurology

Report of the EAN SPN/ESNCH/ERcNsono Neuro-POCUS Working Group

Point-of-Care-Ultraschall in der Neurologie

Bericht der EAN SPN/ESNCH/ERcNsono Neuro-POCUS Arbeitsgruppe

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ABSTRACT

In the last decade, ultrasound examination in neurology has been undergoing a significant expansion of its modalities. In parallel, there is an increasing demand for rapid and high-quality diagnostics in various acute diseases in the prehospital setting, the emergency room, intensive care unit, and during surgical or interventional procedures. Due to the growing need for rapid answers to clinical questions, there is particular demand for diagnostic ultrasound imaging. The Neuro-POCUS working group, a joint project by the European Academy of Neurology Scientific Panel Neurosonology, the European Society of Neurosonology and Cerebral Hemodynamics, and the European Reference Centers in Neurosonology (EAN SPN/ESNCH/ERcNsono Neuro-POCUS working group), was given the task of creating a concept for point-of-care ultrasound in neurology called “Neuro-POCUS”. We introduce here a new ultrasound examination concept called point-of-care ultrasound in neurology (Neuro-POCUS) designed to streamline conclusive imaging outside of the ultrasound center, directly at the bedside. The aim of this study is to encourage neurologists to add quick and disease-oriented Neuro-POCUS to accompany the patient in the critical phase as an adjunct not a substitution for computed tomography, magnetic resonance imaging, or standard comprehensive neurosonology examination. Another goal is to avoid unwanted complications during imaging-free periods, ultimately resulting in advantages for the patient.

ZUSAMMENFASSUNG

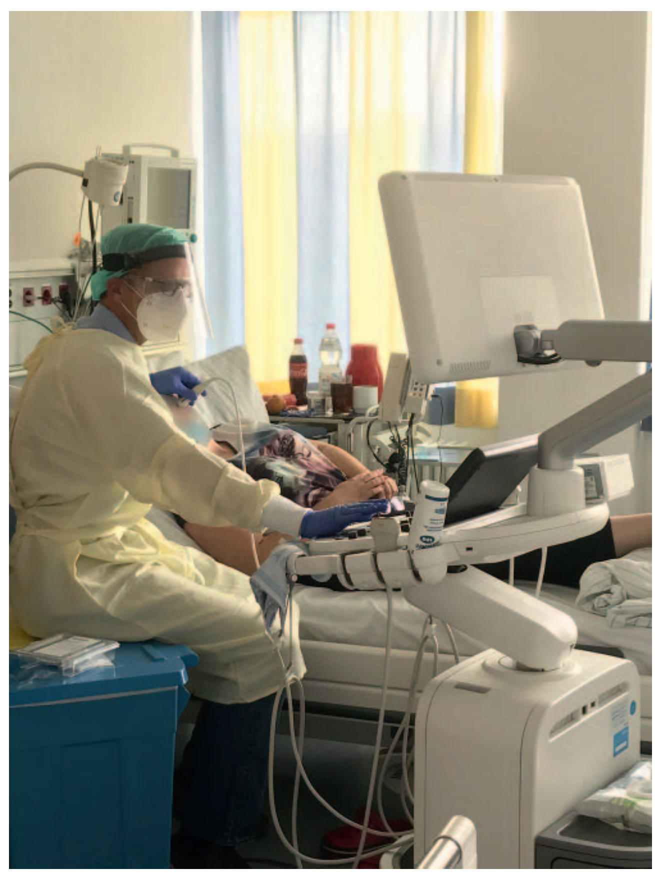
Im letzten Jahrzehnt hat die Ultraschalldiagnostik in der Neurologie eine deutliche Ausweitung ihrer Modalitäten erfahren. Parallel dazu steigt der Bedarf an schneller und qualitativ hochwertiger Diagnostik bei verschiedenen akuten Erkrankungen sowohl im prähospitalen Umfeld, in der Notaufnahme, auf der Intensivstation und bei chirurgischen oder interventionellen Eingriffen. Die Neuro-POCUS Working Group, eine gemeinsame Aktivität des European Academy of Neurology Scientific Panel Neurosolonogy, der European Society of Neurosonology and Cerebral Hemodynamics und der European Reference Centers in Neurosonology (EAN SPN/ESNCH/ERcNsono Neuro-POCUS Working Group) hat sich zum Ziel gesetzt, ein Konzept des Point-of-Care-Ultraschalls in der Neurologie mit dem Namen „Neuro-POCUS" zu erstellen. Die bildgebende Diagnostik wird durch den wachsenden Bedarf an schnellen Antworten auf klinische Fragen besonders herausgefordert. Wir stellen hier ein neues Konzept der Ultraschalluntersuchung vor, den sogenannten Point-of-Care-Ultraschall in der Neurologie (Neuro-POCUS), der eine aussagekräftige Diagnostik fernab des Ultraschalllabors direkt am Krankenbett ermöglichen soll. Ziel dieser Arbeit ist es, Neurologen zu ermutigen, den Patienten in der kritischen Phase mit einem schnellen und krankheitsorientierten Neuro-POCUS zu begleiten und nicht als Ersatz für die Computertomographie, die Magnetresonanztomographie oder die umfassende neurosonologische Standarduntersuchung zu dienen. Ein weiteres Ziel besteht darin, unerwünschte Komplikationen innerhalb bildgebungsfreier Zeiträume zu vermeiden und das outcome des Patienten Vorteile zu verbessern.

Introduction

In the last decade, neurosonology (ultrasound examination in neurology) has been undergoing a significant expansion of its modalities, including brain and atherosclerotic plaque perfusion imaging, elastography, fusion imaging, super-fast Doppler, blood flow volumetry, digital image analysis in, e. g., transcranial sonography and carotid plaque imaging, and translation of the cerebral hemodynamics and vasoregulation into clinical decision making [1–4]. This development has led to increased diagnostic confidence and, thus, a better quality of care. However, it places high demands regarding ultrasound devices, sonographer competence, and, above all, the required critical examination duration [5, 6].

In parallel, various acute diseases increasingly require rapid and high-quality diagnostics to be able to initiate treatment, starting in the prehospital setting, the emergency department, intensive care medicine, and during surgical or interventional procedures. There is particular demand for ultrasound examinations, exceeding the combined number of computed tomography, X-ray, and magnetic resonance imaging procedures. In addition, due to the high diagnostic accuracy, widespread availability, low price, noninvasiveness, and mobility of ultrasound devices, the use of sonographic examination is often the first choice for these patients. Thus, a new ultrasound examination concept as a method that provides quick answers to specific clinical questions emerged, instead of a complete standard examination. This concept was called point-of-care ultrasound (POCUS).

With the recent progress in efficient therapies, the need for a rapid answer to a clinical question applies to various acute neurological conditions. In addition, the COVID-19 pandemic has increased the need for neurosonological point-of-care diagnostics in order to meet hygienic concepts, that are ideally bedside, and to minimize the risk of virus transmission by minimizing the sonographer's total exposure – ▶ **Fig. 1**. Thus, the Neuro-POCUS working group, a joint project of the European Academy of Neurology Scientific Panel of Neurosonology, the European Society of Neurosonology and Cerebral Hemodynamics, and the European Reference Centers in Neurosonology (EAN SPN/ESNCH/ERNsono Neuro-POCUS working group) was given the task of creating a concept for point-of-care ultrasound in neurology called "Neuro-POCUS". Nevertheless, the POCUS concept should not replace a comprehensive ultrasound examination, but rather allow physi-



▶ **Fig. 1** Neuro-POCUS examination in a patient with suspected COVID-19 infection.

cians immediate access to clinical ultrasound for rapid and direct solutions [7].

The aim of the paper is to give the basics, concept, and outline of potential indication fields for Neuro-POCUS.

What is Neuro-POCUS?

The definition of POCUS is slightly diverse in published documents. Nevertheless, most definitions share some fundamental features, in particular the performance of ultrasound by the clinician in charge of the patient's therapy on-site, regardless of where he or she may be located [7, 8]. Unlike ultrasound examination of most parts and organs of the human body, neurosonological examination of the head, neck, and neuromuscular system is not part of POCUS for intensivists, anesthesiologists, and general practitioners. Thus, the Neuro-POCUS working group defines Neuro-POCUS as a specific part of POCUS. After searching existing POCUS definitions in the databases MEDLINE (via PubMed), Web of Science, Google Scholar, we define Neuro-POCUS as a goal-directed/focused portable ultrasound examination of the head, neck, and/or musculoskeletal system, performed at the patient's bedside or where the patient is being observed/treated, in order to obtain a prompt answer to a specific clinical question related to neurological symptoms in real time for guiding diagnostics (e. g., symptom-based examination) and treatment, including therapeutic supporting procedures (e. g., image guidance). Ultrasound equipment can be delivered wherever the patient is located and, thanks to the advances in computational power, high-quality portable ultrasound machines are now widely available.

Why is Neuro-POCUS performed?

The treatment options in various acute neurological diseases have significantly advanced in the past two decades. The resulting work densification calls for goal-directed diagnostics, as fast and efficient diagnostics are prerequisites for specific treatment pathways, including their modification, both of which can significantly improve treatment success and, therefore, the prognosis of patients [9]. For safety reasons during transport, for faster answers to clinical questions, or for other reasons of convenience, it is frequently more appropriate to bring ultrasound to the patient instead of the patient to the ultrasound department. Thus, Neuro-POCUS has high potential for playing a key role in clinical neurology questions, not only in the emergency room but also in the intensive care unit (ICU), stroke unit, surgery ward, and outpatient clinic or in a remote village.

The potential use and benefits of the Neuro-POCUS examination are very broad. The most important areas of use and indications identified by the Neuro-POCUS working group, with examples of clinical questions, machine settings, and examination algorithms, are described below.

Who should perform Neuro-POCUS?

Neurosonology examination is critically dependent on each patient's clinical settings, including working and differential diagnoses. Thus, Neuro-POCUS should ideally be performed by a physician who has experience in clinical neurology, as well as in at least the specific area of neurosonology that is in question. Otherwise, close cooperation between all involved specialists is mandatory. Nevertheless, it needs to be emphasized that questions with different degrees of complexity require different levels of neurosonology experience. The requirements for each Neuro-POCUS question include substantial theoretical knowledge of the subject, clinical and anatomical knowledge, technical knowledge including sensitivity and specificity of the technique applied, and sonographic skills, including having examined a sufficient number of patients with relevant/similar diagnoses using recommended sonographic modalities.

Where to perform Neuro-POCUS?

In principle, the Neuro-POCUS examination can be performed in any setting where the patient is located and the clinical workflow is immediately driven by ultrasound findings, depending only on the ultrasound equipment's size and mobility and the patients themselves. It might be applied at the very first contact with a doctor/paramedic at the patient's home, in an ambulance, or even in a helicopter [8, 10, 11], bedside in a hospital, in the emergency room [12–14], ICU [13–16], stroke unit, neurology, surgery or other hospital wards, outpatient clinic, or in a remote village by means of telemedicine [17, 18].

Neuro-POCUS could be used in the four basic scenarios:

1) Triage in the emergency room

Emergency wards are often the primary place in which neurologists have contact with patients presenting acute neurological symptoms, and neurosonology examinations can detect pathological findings in various diseases and pathological conditions (► **Table 1**, indications 1, 2, 3, 7, and 8). Stroke diagnosis is the prevailing application as, given the elderly population, vascular pathologies are among the most common pathological findings. Although it should not delay CT or MR imaging and revascularization treatment, Neuro-POCUS may rapidly provide information about a large vessel occlusion or significant stenosis or suggest a carotid dissection often even in agitated patients, thereby guiding the examiner to specific treatments, e. g., CT imaging under sedation [19]. In acute amaurosis, US can help with the differential diagnosis and allow faster treatment [20].

A recent meta-analysis of 45 studies, which analyzed 18 304 acute stroke patients and employed vascular neurosonography beyond CTA, MRI, and/or digital subtraction angiography, found an ipsilateral non-stenotic carotid plaque in 51 % of patients (95 % CI: 45–59) [21]. Moreover, the Neurosonology in Acute Ischemic Stroke study group published occlusion rates of 33 % to 66 % in cervical and/or intracranial brain-supplying arteries detected by ultra-early duplex sonography [22].

Elevated intracranial pressure (ICP) is a serious and relatively common pathological condition that may lead to neurological and ophthalmological symptoms, which can be life-threatening or highly debilitating, and is easily treatable using various neurosonographic methods [23, 24].

Patients with suspected cranial trauma or peripheral nerve trauma represent a significant percentage of patients in the emergency room [25]. Sonography might help detect both peripheral nerve lesions and complement CT scans in traumatic brain injury

▶ **Table 1** List of potential indications for the Neuro-POCUS examination.

No.	Clinical situation/ symptoms/diagnosis	Pathological findings that may be detected by Neuro-POCUS examination
1.	Acute stroke (incl. transient ischemic attack), stroke prevention and stroke mimics (e. g., dizziness, paresthesia, disturbance of consciousness)	Acute large artery occlusion, including central retinal artery occlusion [5, 6, 10, 19, 20, 26, 28, 44, 46, 49, 54, 58–60]
		Recanalization of occluded artery [5, 13, 22, 26–28, 49]
		Arterial reocclusion [5, 13, 26, 61]
		Arterial dissection [5, 27, 62]
		Vasospasm/aneurysm [5, 7, 14, 23, 31, 63]
		Intracerebral hemorrhage [64–66]
		Arterial stenosis [5, 33, 44, 49]
		Microembolization to cerebral arteries [26, 37–40, 42, 52, 53, 67, 68]
		Malignant brain edema [14, 23, 60]
		Hyperperfusion syndrome [2, 5, 49, 60, 69, 70]
		Intracranial flow acceleration in sickle cell disease [71]
2.	Impaired consciousness (qualitative and quantitative) or unconsciousness	Basilar artery occlusion [5, 19, 44, 72–74]
		Local increase in blood flow velocities in the intracranial arteries and/or increased pulsatility and/or resistance indices as a sign of neuroinfection/vasculitis (meningitis, encephalitis) [75, 76]
		Intracranial hypertension [9, 14, 24, 59, 77, 78]
		Local increase in blood flow velocities in the intracranial arteries as a sign of posterior reversible encephalopathy syndrome/acute hypertensive encephalopathy [13]
3.	Headache	Local increase in blood flow velocities in the intracranial arteries and/or decreased pulsatility and/or resistance indices as a sign of migraine [79–81]
		Local increase in blood flow velocities in the intracranial arteries as a sign of reversible cerebral vasoconstriction syndrome, vasospasm [31, 32]
		Arterial dissection [5, 27, 62]
		Local increase in blood flow velocities in the intracranial arteries and/or increased pulsatility and/or resistance indices as a sign of neuroinfection/vasculitis (meningitis, encephalitis) [9, 14, 24, 59, 77, 78] Giant cell arteritis with halo sign [82]
4.	Abnormal shunts	Detection of the right-left-shunt, intracardiac/extracardiac paradoxical embolism [26, 83–85]
		Quantification of right-left shunt [84]
		Detection of the residual right-left shunt after patent foramen ovale or pulmonary arterio-venous malformation closure [86, 87]
		Detection of the dural fistula [88, 89]
5.	Surgery and intraarterial interventions	Monitoring of changes in cerebral blood flow (hypoperfusion/hyperperfusion) [16, 24, 31, 32]
		Microemboli detection [26, 37–40]
		Detection of residual flow in arteriovenous malformation or aneurysm after embolization/clipping/coiling, etc. [90, 91]
		Monitoring of third ventricle diameter in hydrocephalus [15, 16, 92]
6.	Lumbar, venous, and arterial puncture, intramuscular/intraglandular Botulinum toxin injection	Find the optimal way for puncture [41, 93, 94]
		Venous thrombosis detection [95, 96]
7.	Intracranial hypertension and brain death	Midline shift detection and monitoring [14–16, 24, 97]
		Optic nerve papilloedema [77, 98]
		Optic nerve sheath diameter measurement [9, 15, 16, 59, 77, 78, 98]
		Measurement of change in the width of ventricles [14–16, 92]
		Monitoring of intracranial pressure using pulsatility and resistance indices (in the middle cerebral artery) [14–16, 24, 98]
		Brain death diagnostics [9, 14, 35, 36, 99]
		Hydrocephalus, measurement of ventricles [15, 16, 92]

▶ Table 1 (Continuation)

No.	Clinical situation/ symptoms/diagnosis	Pathological findings that may be detected by Neuro-POCUS examination
8.	Cranial trauma and peripheral nerve injury	Intracranial/intracerebral hemorrhage [92]
		Midline shift [14–16]
		Detection of increased intracranial pressure [9, 14–16, 24, 59]
		Vasospasm [7, 63, 100, 101]
		Peripheral nerve lesions (nerve disruption, edema, oppression) [25, 102, 103]

(e. g., intracranial/parenchymal hemorrhage, midline shift, increased ICP, or vasospasm) [13, 25].

2) Examination in the ICU/stroke unit

Noninvasive neuromonitoring with bedside neurosonography plays an important role in the ICU and, especially, in stroke units (▶ **Table 1**, indications 1,2,3,6,7, and 8). It can be used in acute ischemic stroke patients to monitor arterial recanalization during systemic thrombolysis, after endovascular treatment, as well as the spontaneous course of the disease [26, 27]. Using neurosonology examination in the acute phase of ischemic stroke in patients treated with thrombolysis has been associated with a better outcome, perhaps reflecting a potential impact on patient management [28–30]. In stroke patients with acute deterioration of their neurological status, bedside neurosonological examination can rapidly detect several pathologies that may cause this worsening (e. g., arterial re-occlusion, microembolic signals [MES] and recurrent stroke, parenchymal/intracranial bleeding, hyperperfusion syndrome, malignant brain edema, or vasospasms) [31, 32]. Neuro-POCUS might also be helpful in rapid identification of the specific cause of ischemic stroke bedside, such as arterial dissection or cerebral MES suspicious for acute endocarditis, which may lead to optimization of treatment without time delay. In general, early detection of the stroke cause is essential for early secondary prevention treatment [33].

Neurosonology, especially TCD examination, plays an important role in patients with acute subarachnoid hemorrhage by early detection of complications, such as vasospasm, hyperperfusion, hydrocephalus, and rising ICP [34]. Monitoring intracranial hypertension and the effect of treatment is among the most important roles of bedside neurosonology examination. Neurosonology (with the possibility of serial examination) is also useful for early cerebral circulatory arrest diagnostics, especially in organ donation after brain death [35, 36].

3) Control and support during interventions

Besides monitoring arterial recanalization in acute stroke patients using different methods (e. g., intravenous thrombolysis, endovascular mechanical thrombectomy, stenting, carotid revascularization), as mentioned above, specific sonographic applications may also be helpful to monitor various interventions (▶ **Table 1**, indications 5 and 6). TCD monitoring can be used for the early detection of MES or cerebral hypoperfusion during cardiac surgery, coronary artery stenting, carotid artery endarterectomy or stenting, orthopedic surgery, or other interventions with a high risk of stroke [37–40]. Duplex sonography can support finding the optimal route during lumbar, arterial, or venous puncture [41]. In general, in all such situations the Neuro-POCUS concept is typically employed instead of standard comprehensive neurosonology examination in the ultrasound department.

4) Differential diagnosis and decisions regarding further management in ambulatory neurology

Although there is currently no common reason in ambulatory neurology for patients to be indicated for Neuro-POCUS instead of standard neurosonological examination, the COVID-19 pandemic has shown that not only the clinical condition of patients but also the risk of spreading the infection may limit patient transport. Moreover, rapid neurosonology examination may play an important role in ambulatory neurology for differential diagnosis and decisions regarding further management of selected patients with various neurological symptoms (▶ **Table 1**, indications 1, 3, and 4). Examples might be rapid tracking for significant cerebral arterial circulation lesions in patients with transient symptoms (e. g., TIA due to large vessel disease, Bow Hunter's syndrome, subclavian steal syndrome), helping to distinguish arterial dissection, or detection of transient vasospasms in patients with headache.

When to perform Neuro-POCUS?

Neuro-POCUS examination is indicated mainly when the physician or consultant responsible for a patient´s care decides that transporting the patient to the ultrasound department is not feasible (e. g., during interventional procedure) or is risky due to time delay of treatment or intervention, unstable patient condition, or spreading of infection, or when a rapid answer is needed or beneficial for a patient.

The portability of ultrasound devices makes it possible to select the optimal timing, according to the best incorporation of the information in the clinical workflow of the patient with neurological symptoms or the acutely unwell patient, during intensive care rounds, or during and after several interventions. The optimal time for performing the Neuro-POCUS examination is immediately after a clinical question is raised that can be answered by neurosonology examination, without undue delay.

What is required to perform Neuro-POCUS?

Neuro-POCUS requires a portable (mobile) duplex (Doppler plus echography imaging) ultrasound device that can potentially access the patient at the bedside, in both the prehospital and hospital settings. This equipment allows studying of the cervical and/or intracranial vessels, as well as examining of other body parts. Thanks to the advances in clinical ultrasound, we have access to high-quality, portable duplex sonographic devices, offering high resolution and clearly defined images. The machine and battery stand-by/fast power-up mode has developed to allow true routine and widespread use at the patient's bedside. The TCD machines, which have no echography imaging, are useful mainly for cerebral hemodynamics monitoring because the small Doppler probes can be mounted bilaterally in a cranial helmet, allowing continuous blood flow velocity and MES monitoring without operator assistance [42].

The requirements for probes and imaging quality do not differ from classical neurosonological examination. For extracranial (cervical) vessel examination, a medium-frequency (5–12 MHz; optimally 3–15 MHz) linear array probe is required. A high-frequency 12–18 MHz linear array probe is required for superficial temporal artery and musculoskeletal examinations, as well as for small children. A low-frequency (2.5 MHz; optimally broad-band 1–5 MHz) phased array is required to examine intracranial arteries and/or intracranial parenchymal structures using TCD, TCCS, or transcranial B-mode sonography (TCS). For continuous monitoring of MES as well as to obtain information about cerebral hemodynamics during therapeutic interventions, we need a TCD device with 2-MHz monitoring probes with customized software.

Whenever the quality of the temporal bone window is low, insufficient, or absent, or a large intracranial artery occlusion is suspected, an ultrasound echocontrast agent (UEA) may improve the sensitivity and specificity of the examination [43].

How to perform Neuro-POCUS?

The physician/neurosonographer should perform a clinically oriented fast-track examination at the patient's bedside in a convenient supine position, mostly but not exclusively from behind the patient's head or at the patient's side. In case patient positioning is not possible due to the patient's medical condition or if there is no time to position the patient, Neuro-POCUS can be performed in any patient position that allows the necessary ultrasound application. Depending on time, the clinical question, and requirements, duplex sonography of cervical vessels, orbit, intracranial vessels, parenchyma, or even other targets is performed.

For example, a Neuro-POCUS cerebrovascular examination in acute stroke should be done as a "fast track" study [5]:

1. the examination is focused on the symptomatic vascular territory where the examination should start,
2. case-specific clinical competence is necessary for planning the steps of the examination,
3. the examination might be performed even after the start of therapy to ensure the earliest possible initiation of treatment,
4. despite the time pressure, emergency diagnostics should be performed both extra- and intracranially when it is suitable for the diagnosis; but only limited vessels usually need to be examined to answer the acute clinical question, in contrast with standard comprehensive neurosonology [44].
5. color duplex sonography allows an anatomical overview and significantly simplifies and speeds up the identification of vessel occlusion. In addition, clear documentation of the findings is possible at the push of a button,
6. it is possible to adapt the workflow of the examination whenever patients are agitated, confused, anxious, or aphasic.

Also, for TCD, the time of Neuro-POCUS TCD monitoring is set individually by the clinician and sonographer to answer the target clinical question compared to standard TCD monitoring [45].

In general, the choice of the scope of the neurosonological examination depends on the clinical question and the condition of the patient.

During the COVID-19 pandemic, special attention must be paid to hygiene concepts. The ultrasound providers (physicians, sonographers) involved in the care of stroke patients with/without COVID-19 must assure safety, avoid spreading infection, and ensure the delivery of hyper-acute treatment [46].

Creating Neuro-POCUS clinical questions

The implementation of Neuro-POCUS with contracting target questions should consider the setting (e. g., hospital/pre-hospital; intensive/semintensive/regular care), the clinical scenario (e. g., acute/chronic; stroke/headache), alternative investigations available (e. g., CT/CTA, MRI/MRA), its impact on diagnosis, and its therapeutic implications (▶ **Table 2**) [47]. For example, the role of Neuro-POCUS in assessing a large vessel occlusion in a stroke patient in the prehospital setting where no other imaging modalities are available is much different than its role when evaluating the same patient in a tertiary care center.

The sonographer applying Neuro-POCUS in the clinical setting should be well acquainted with the ultrasound protocol and technical requirements, to be able to answer a specific clinical question while also deeply understanding the inherent advantages and limitations of ultrasound compared to other imaging techniques, for a given clinical setting. Finally, before initiating any Neuro-POCUS protocol, the examiner should set a clear target for the specific information to be obtained from the examination, the translation of the provided information to patient care, and whether the information provided by Neuro-POCUS is expected to have an impact, and at which level, on the patient's outcome. Examples of potential Neuro-POCUS questions can be found in ▶ **Table 3–5** and in 2 cases in the supplemental material and ▶ **Fig. 2, 3**.

Discussion

POCUS was described as "the stethoscope of the future" ten years ago, and today it is becoming an integral tool for clinical decisions in patient management [34]. POCUS examination is becoming an exceptionally valuable tool both in Europe and worldwide. In the United States, POCUS is applied in outpatient and inpatient departments as an urgent noninvasive diagnostic tool for multi-organ ultrasound diagnostics of lung, skeletal, muscular, and

▶ **Table 2** Recommended methodology for creation of Neuro-POCUS clinical questions with examples.

(P)opulation		**(I)ntervention**		**(C)omparator**		**(O)utcome**
Symptoms/disease	**Location**	**Neuro-POCUS protocol**	**Timing**	**Other diagnostic method(s)**	**Considerations**	**Role**
Stroke	Ambulance/ ED/SD unit/ ICU/ward	TCD/TCCS +/– Carotid/ vertebral US	Urgent	CT/CTA MRI/MRA	Radiation exposure, absolute/relative contraindications, cost, availability	Establish diagnosis & guide treatment
Headache	Ambulance/ ED/ward	TCD/TCCS Carotid/vertebral/ superficial temporal artery US	Urgent	CT/CTA MRI/MRA	Radiation exposure, absolute/relative contraindications, cost, availability	Rule out vascular abnormalities (e. g., dissection, RCVS) & cerebral edema, diagnosis of giant cell arteritis
Impaired consciousness	Ambulance/ ED/SD unit/ ICU/ward	TCD/TCCS	Urgent	CT/CTA MRI/ MRA	Radiation exposure, absolute/relative contraindications, cost, availability	Rule out vascular abnormities (e. g., occlusion, vasospasm) & cerebral edema
		TCD/ carotid vertebral US or TCCS/ carotid vertebral US	Semi-urgent	CT/CTA Perfusion scintigraphy/ SPECT	Exposure to contrast agents, need of transportation of mechanically respirated patients, cost, availability	Proof of cerebral circulatory arrest
Other neurological symptoms	ICU	Transorbital sonography	Semi-urgent	Fundoscopy	Technical challenges, use of mydriatics	Monitoring/follow-up of intracranial pressure
Subacute Sensory/ motor symptoms in extremities	ED/SD unit/ ICU/ward	Peripheral nerve US	Semi-urgent	EMG	Availability	Diagnosis of neuropathies/plexopathies & prognostication
		Muscle US	Semi-urgent or Elective	CT, EMG	Availability	Intramuscular botulinum toxin injection in painful nerve compression syndromes (e. g., thoracic outlet syndrome, piriformis syndrome)
Dysphagia with hypersalivation	ED/SD unit/ ICU/ward	US of parotid and submandi-bular gland	Semi-urgent or Elective	Injection without US guidance	Availability	Intramuscular botulinum toxin injection in relative hypersalivation due to dysphagia with imminent aspiration

CT – computed tomography; CTA – computed tomography angiography; DSA – digital subtraction angiography; ED – emergency department; EMG – electromyography ICU – intensive care unit; MRI – magnetic resonance imaging; MRA – magnetic resonance angiography; POCUS – point-of-care ultrasound; RCVS – reversible cerebral vasoconstriction syndrome; SD – step-down unit; SPECT – single photon emission computed tomography; TCCS – transcranial color-coded duplex sonography; TCD – transcranial Doppler; US – ultrasound.

▶ **Table 3** Examples of Neuro-POCUS key findings: Patients with acute stroke symptoms.

Diagnosis	TCCS finding	Confirmation	Tips & limitations
MCA main stem occlusion	Absence of ipsilateral MCA color-coded in red [skill level low]	Visualization of the ipsilateral and contralateral ACA (blue and red)	Perform flow measurements in order not to miss MCA low flow
Carotid-T occlusion	Absence of ipsilateral MCA color-coded (red) and ACA (blue) [skill level low]	Visualization of the contralateral ACA (red) and ipsilateral PCA	
Basilar artery occlusion	Absence of both PCAs in the P1-segments (= top of the basilar) [skill level low]	Visualization of the anterior circulation (MCA, ACA)	Visualization of both P2-segments in a non-comatose patient may be due to fetal type origin of the PCA
ICA occlusion or high-grade stenosis	Reversal of flow in the ipsilateral ACA [skill level moderate]	"Musical murmurs" in the anterior communicating artery	
Space-occupying lesions (ICH, subdural hematoma or brain tumor, etc.)	Midline displacement of the third ventricle [skill level high]	Increase of pulsatility index in the MCAs	The finding may be non-specific and should correlate with the patient's neurological status
ICH	Hyperechoic mass lesion [skill level high]	Location in the basal ganglia and thalamus has the highest sensitivity	ICH detection is difficult, as hyperacute ICH, cortical, cerebellar, frontal, and occipital ICH can be missed

Minimal requirement is an ultrasound machine: 1.5–3 MHz phased array transducer
Location: prehospital, emergency ward, stroke unit, outpatient clinic
Diagnostic boost: application of an echo-enhancing agent increases diagnostic confidence, increases diagnosis in a poor temporal bone window, and saves time
ACA – anterior cerebral artery; ICA – extracranial internal carotid artery; ICH – intracerebral hemorrhage; MCA – middle cerebral artery; PCA – posterior cerebral artery.

▶ **Table 4** Example of Neuro-POCUS-specific clinical questions: Is the intracranial pressure increased?

	Parenchymal diagnostics	Hemodynamic findings	Orbital sonography
Modalities/techniques/modes	B-mode Monitoring of midline shift and third ventricle (malignant cerebral infarction, intracerebral hemorrhage, hydrocephalus)	TCD- and TCCS-derived parameters, especially increased pulsatility index [104]	B-mode
Minimal level of experience required	Intermediate skill (US > 100 measurements and > 20 compared with the CT scan)	Intermediate skill (> 25 examination)	Intermediate skill (> 15 examination)
Location/scenario	Neurointensive care/stroke unit Emergency department	Prehospital Emergency department Neurointensive care/stroke unit	Prehospital Emergency department Neurointensive care/stroke unit
Minimal requirements for ultrasound probe	2–4 MHz probe	2–4 MHz probe	At least 7.5 MHz linear probe, at best > 12 MHz MI 0.2 reduction
Restricted examination protocol		Measurement of PI (or RI) in one intracranial artery (optimally middle cerebral artery) bilaterally	Depth of 3 mm behind the retina
Cut-off values	Third ventricle diameter (7 and 10 mm for subjects < 60 and ≥ 60 years of age, respectively) [55]	Normal values = 0.7 +-1 PI values above 2 with normal mean arterial blood pressure in a normocapnic patient can indicate elevated ICP	Normal values 5.4 ± 0.6 mm [105] Abnormal values between 6–7 mm
Pitfalls	Lack of adequate acoustic temporal bone window	Hemicraniectomy	Optic nerve atrophy Glaucoma Ocular trauma

CT – computed tomography; ICP – intracranial pressure; PI – pulsatility index; RI – resistance index; TCCS – transcranial color-coded duplex sonography; TCD – transcranial Doppler; US – ultrasound.

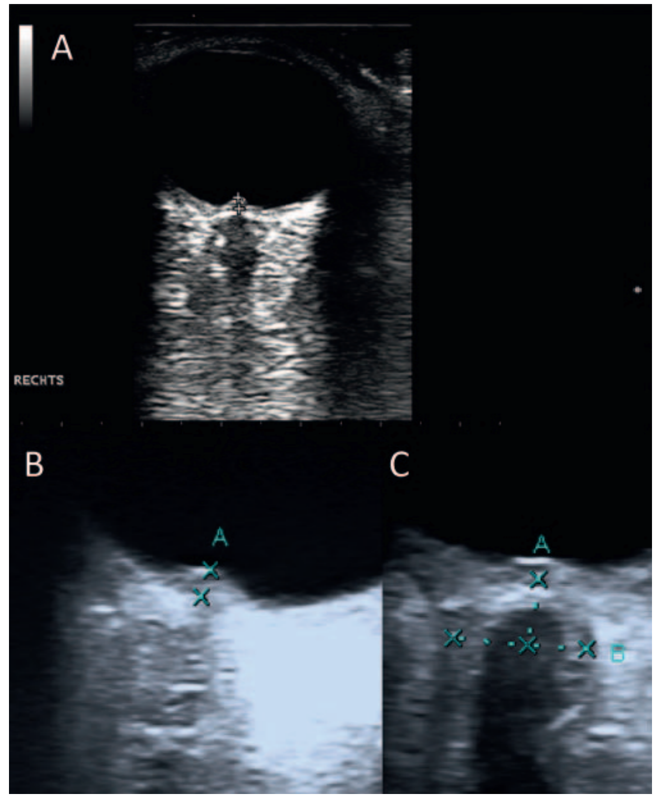
▶ **Table 5** Example of Neuro-POCUS-specific clinical questions: Is a shunt indicated during a carotid endarterectomy?

	Hemodynamic findings
	TCD (TCCS) monitoring
Minimal level of experience required:	Low skill (5 repeated examinations or TCD monitoring)
Location/scenario:	Hospital – operating room
Time (when is Neuro-POCUS indicated):	During carotid endarterectomy (clipping carotid artery)
Minimal requirements for ultrasound machine:	TCD/TCCS machine
Minimal requirements for ultrasound probe:	2-MHz TCD probe
Restricted examination protocol	Continuous or repeated measurement of PSV and MFV in MCA
Cut-off values during clamping predicting post-interventional new brain ischemic lesion:	MFV in MCA < 25 cm/s has SE = 100 % and SP = 69 %. MFV in MCA < 6 cm/s has SE = 22 % and SP = 100 %. Decrease of MFV in MCA compared with baseline >48 % has SE = 100 % and SP = 86 %. Decrease of MFV in MCA compared with baseline >70 % has SE = 78 % and SP = 100 %. [106]
Pitfalls:	Missed signal due to movement of the probe Inaccurate measurement of PSV and/or MFV due to inadequate acoustic temporal bone window Drop of blood flow velocity due to decrease/low blood pressure

ICA – internal carotid artery; MCA – middle cerebral artery; MFV – mean flow velocity; PSV – peak systolic velocity; SE – sensitivity; SP – specificity; TCCS – transcranial color-coded duplex sonography; TCD – transcranial Doppler.

abdominal pathologies, among others, and is integrated into medical schools and residency training programs [48]. Neurological and neurovascular disease management can also clearly benefit from Neuro-POCUS, thereby improving patient outcome.

Compared to standard neurosonology examination performed in the ultrasound department, Neuro-POCUS provides the possibility of getting a prompt answer to a well-defined question by noninvasive ultrasound earlier and in real-time at the patient's bedside. This is particularly essential in patients who need rapid diagnostics prior to urgent treatment initiation (e. g., acute stroke) [28, 44, 49] and in critically ill patients where transport is associated with a higher risk of complications (e. g., intubated patients on artificial ventilation in the ICU) [14, 23]. The second main difference between the Neuro-POCUS and the standard neurosonology examination is that Neuro-POCUS uses a restricted examination protocol. This protocol is question-related to save time without decreasing the accuracy. Nevertheless, it should be

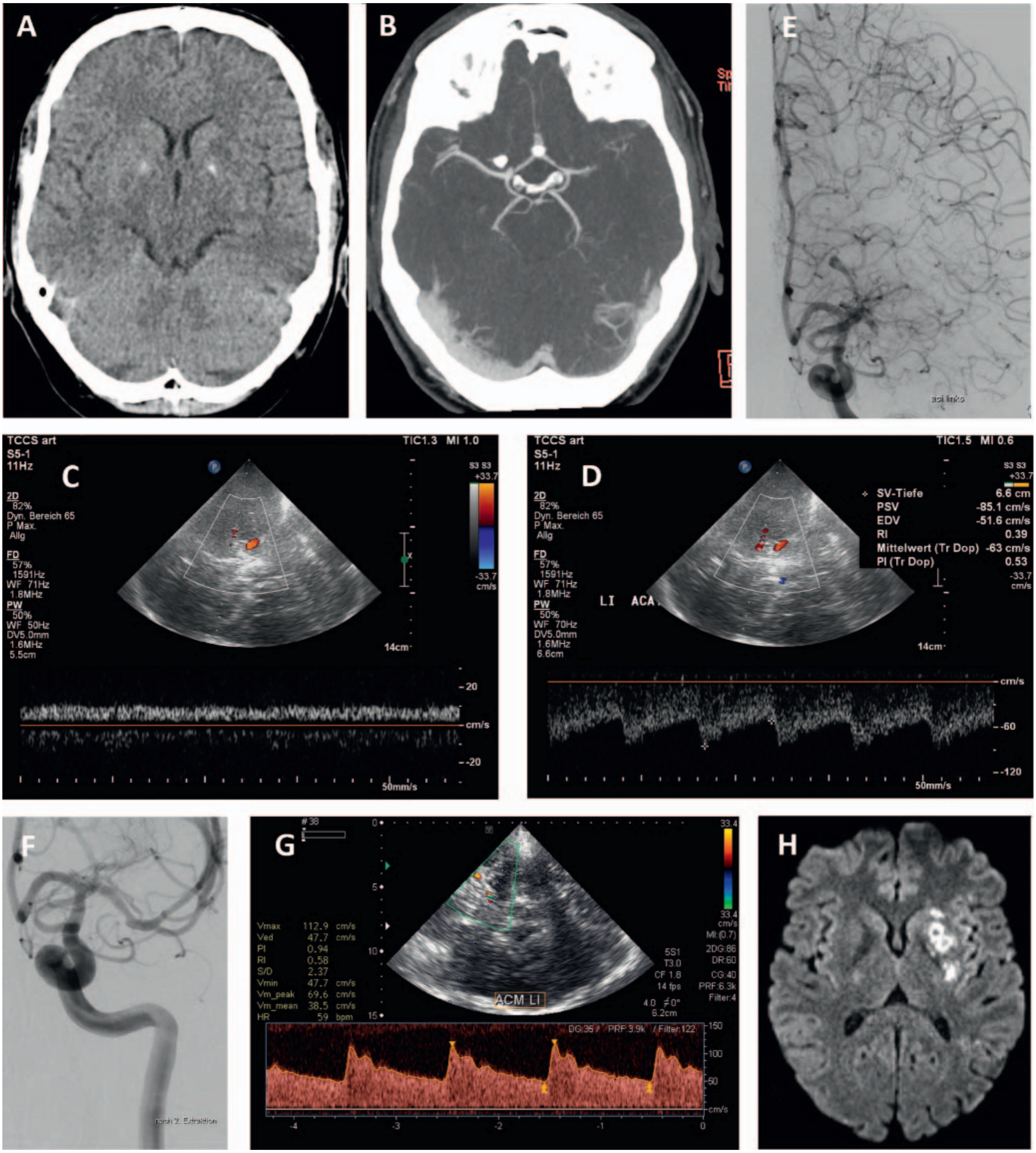


▶ **Fig. 2** Neuro-POCUS examination of orbita in patient with idiopathic intracranial hypertension **A** with a detection of papilloedema 1.3 mm **B** and a distal enlargement of the optic nerve sheath diameter of 6 mm **C**.

noted that only future studies may answer the question whether Neuro-POCUS results in better patient outcome than in a standard neurosonological department in specific situations, especially in cases where the indication for Neuro-POCUS is not yet routinely considered.

Thanks to the rapid bedside examination, Neuro-POCUS is especially useful in a case of emergent and urgent neurological disorder to modify the diagnosis and guide ongoing therapy, so that the management plan can be corrected without delay. Neuro-POCUS also significantly differs from the "ICU-sound" protocol for so-called "head-to-toe" ultrasound (optic nerve, thorax, heart, abdomen, and venous system), which was developed for a rapid global assessment of critically ill patients to increase diagnostic accuracy (screening protocol) and may lead to incidental findings unrelated to the current disease. Moreover, as it is easily repeatable in case the patient's condition changes, Neuro-POCUS might maximize benefit, reduce health care costs, and help avoid unnecessary harm, such as radiation, and repeated CT/CTA, MR, or digital subtraction angiography examinations.

Ultrasound examination is an operator-dependent diagnostic method, and the reliability and validity of the achieved results depend on the sonographer's skills and experience. Bedside neurosonology examination is today frequently applied by operators confined to a very specialized setting and a restricted question (e. g., emergency physician, anesthesiologist, intensivist, or technologists). The examination is performed by operators working at



▶ **Fig. 3** A case of complementary neuroimaging in a patient with acute stroke. Brain CT: a left insular infarction **A**. CT angiography: a middle cerebral artery occlusion **B**. Transcranial color-coded duplex sonography: absence of flow in the middle cerebral artery and good flow in a deep middle cerebral vein **C** and decreased resistance index in the ipsilateral anterior cerebral artery is suggestive of collateral flow **D**. Digital subtraction angiography: excessive anterior cerebral artery collaterals **E**. Digital subtraction angiography: restored middle cerebral artery blood flow **F**. Transcranial color-coded duplex sonography: blood flow without hyperperfusion in the middle cerebral artery **G**. Diffusion-weighted magnetic resonance imaging: subinsular lesions **H**.

the point of care who are specifically trained in a selective ultrasound application but often do not have comprehensive experience in general neurosonology. Thus, the Neuro-POCUS questions must consider the sonographer's level of experience, and a sonographer with an appropriate level of experience should be called to perform the Neuro-POCUS examination and answer a relevant, well-defined question [49].

Introducing Neuro-POCUS into daily clinical practice has become even more important during the COVID-19 pandemic [46, 50]. Since ultrasound examination involves direct contact between the patient and the sonographer, this examination should be considered a procedure with a potentially high risk of COVID-19 transmission. Indeed, a standard neurosonology examination often takes several tens of minutes. However, by using the restricted examination protocol at the bedside, Neuro-POCUS saves significant time and thus reduces the risk of spreading infection.

In the last decade, some new sonographic techniques have become a common part of neurosonology examination. TCD machines with a robotic probe allow rapid detection of blood flow signals from intracranial arteries, assess intracranial autoregulation, and reduce the examination quality's dependence on the sonographer's experience [51]. It can even eliminate the need for a sonographer at the bedside, and the measured values can be assessed remotely (using telemedicine or online) [18]. Automated MES detection is developed to improve the identification, differentiation between types, and quantification of MES [52]. It could be useful to optimize early prevention treatment in patients with ischemic stroke [53] or to optimize surgery or endovascular interventions to minimize the risk of ischemic stroke [54].

Non-imaging transcranial perfusion sonography is another promising ultrasound method. In the future, it could be used bedside in patients with acute stroke to monitor brain perfusion [55]. Great hopes have been placed on the development of artificial intelligence in neurosonology. Developments in robotization, automatic digital image analysis, new software, and diagnostic algorithms are potential ways to improve the reliability, validity, and accuracy of the Neuro-POCUS examination and reduce the dependence on the sonographer's insonation skills and experience [56, 57].

Conflict of Interest

The authors declare that they have no conflict of interest.

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