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High-resolution, field approaches for assessing pain: Ecological Momentary Assessment

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Advances in measurement theory and technology in medicine often provide the ability to examine phenomena formerly undetected (through improved resolution of measurement), to support theoretical progress (by providing the ability to discover new associations), and to enable more efficient studies (by reducing measurement error and increasing statistical power). Although the technology of momentary assessment has been available for years, it could be better used for addressing many questions in pain research. We therefore present this review on methods for collecting patients' pain experiences based on multiple assessments of momentary or near-momentary pain in people's everyday lives. We start with a rationale for the development of the techniques and then discuss selected design features of momentary research that make it particularly suited for pain researchers. This is followed by our take on how momentary designs can add to our understanding of pain. Next, we discuss recent studies that have successfully used momentary methods in pain research. We close by presenting ideas for future development of these methods.

1. Rationale and core principles

There are many reasons for collecting data with an Ecological Momentary Assessment (EMA) design in combination with or in lieu of retrospective questionnaires or interviews. (Momentary techniques go by various names including the Experience Sampling Method,[11,13,52] Ecological Momentary Assessment,[45,46,46,52] Intensive Longitudinal Assessment,[2] and Real Time Data Capture,[48] among others. For ease of exposition, we use the abbreviation EMA to refer to the family of momentary assessments). **Table 1** presents the 4 core principles of EMA and their relevance for the study of pain. First, one may wish to ensure that study results are applicable

to the real world and not limited to artificial or laboratory situations because results obtained in artificial situations often do not generalize to everyday life (ecological validity[5]).

Second, one may be concerned about measurement bias associated with retrospective processes.[3] This is especially likely when information is recalled over "long" periods (at least relative to the salience of the entity reported) and when relevant information is difficult to access.[39] Such circumstances can result in the use of cognitive heuristics to answer questions.[54] Ecological Momentary Assessment minimizes bias and noise by greatly reducing the period asked about.

Third, one may want to be sure that assessments of pain are a representative sampling of peoples' everyday experiences, emphasizing the importance of sampling frameworks for assessments. Just as we know that selection biases[10,24] can occur when sampling individuals for a study, analogous processes can occur with sampling moments. An example makes the point: if we prompted participants regularly at 7 AM, noon, and 6 PM, we would have biased our sample of moments towards detecting appetitive consumption. Considerable attention is therefore paid to sampling schedules in momentary research.

Finally, in almost all EMA studies, respondents are assessed many times. The objective is to capture the ebb and flow of the circumstances or contexts people are exposed to in everyday life, including where they are, what they are doing, whom they are with, and time of day. This allows for the evaluation of within-person effects and the temporal dynamics of interest. We know from laboratory and clinical studies that contextual factors can have considerable effects on pain levels, and EMA allows us to understand naturally occurring contexts.[31]

2. Design of ecological momentary assessment studies: sampling schedules, recall periods, and content

Ecological Momentary Assessment studies typically follow respondents over a period (eg, one week) and signal them throughout each day (eg, 6 times a day) according to a set of sampling rules (eg, randomly scheduled assessments) to respond to a brief set of questions (eg, answering 15 questions through a smartphone app) about the immediate circumstances (eg, pain intensity at the moment). There are dozens of study possibilities formed just by these design choices. The actual parameters chosen for a particular study will be directed by the questions at hand. If the hypothesis was about acute responses to a treatment, for instance, then patients might be asked to answer 10 randomly administered assessments (eg, a brief symptom inventory) each day 3 days before and after the treatment. Treatment studies tracking longer-term changes in

Key features of EMA, their operationalization, and pain relevance.

EMA feature	Operationalization	Pain-related relevance
Measurements are taken in the real-world to ensure ecological validity	Respondents are assessed outside of laboratory or clinical settings to capture people's experiences in their natural environment	Understanding how pain is experienced in daily life
Assessments are made of immediate experience to reduce errors of retrospection	With EMA, respondents assessed about their immediate experience (*"right before the prompt"*) With cEMA, respondents assessed over a brief period (*"since the last prompt"* or *"over the last 2 hours"*)	Avoids rating difficulties for patients Reporting errors due to biases and issues with memory reduced by momentary measurement Rapid dynamics ideally studied with EMA, whereas infrequent occurrences or broader coverage ideally studied with cEMA
Assessment moments are carefully selected to meet the study objectives	A family of sampling schedules are available to meet various study design needs The length and daily density of assessments can be tailored to study design needs	Random sampling is useful for obtaining a representative sample of pain experiences over time Event sampling is useful for evaluating response treatment effect where the event is medication taking (eg, fast-acting and slow-release medications) Hybrid sampling is useful for measuring the timing and duration of treatment side effects, and the frequency and contexts of pain flares
Multiple assessments are taken to enable investigation of within-person associations	Convenient and noninvasive data capture modalities are used for repeated measurement over days and weeks Various data capture modalities are available including specialized watches, PDAs, smartphone apps, and telephone-based interactive voice response*	Can reveal pain temporal dynamics that are relevant for diagnostic purposes and clinical decision-making Can reveal diurnal cyclicity and prolonged episodes of heightened pain intensity Can reveal concurrent or temporally lagged within-person relationships between pain intensity and other pain-relevant constructs including catastrophizing,[21] personality (eg, neuroticism or extraversion[21,22]), mental health (eg, anxiety and depression[14,16]), sleep,[4,26] and activity[12] Identification of contextual factors that alleviate (eg, rest and pleasant activities) or exacerbate (eg, stress and physical activity) pain levels

* Studies using PDAs usually involve providing participants with a designated device to collect the momentary assessments. Smartphone apps allow participants to download the software to collect the assessments on their own device. Telephone-based interactive voice response systems usually involve calling participants through an automated system that lets participants complete the momentary assessments through the phone keypad. EMA, Ecological Momentary Assessment.

symptoms might demand a several-week protocol with a lower frequency of daily assessments to manage participant burden.

Many other features of EMA designs must be considered including the construction of appropriate questions for the intended recall period, the length of each momentary assessment, procedures for reminding participants about missed assessments, determination of compliance rates, handling of missing data, and dealing with technical issues concerning administration modality.[47,53] We focus on 2 topics central to EMA, sampling moments and recall period, to provide a clearer picture of momentary research.

The first is which moments one should sample. Over the years, a handful of schedules have been developed to serve various investigator needs.[43] *Random sampling* schedules are useful for characterizing people's levels of pain, for example, by computing an average from many random pain intensity ratings (Truly random assessments spread throughout the day can result in an uneven temporal spread. For this reason, stratified random sampling is often used, wherein days are divided into segments and an assessment is randomly selected from within that segment). It provides a representative sampling of respondents' lives and is the most commonly used sampling method. *Event-based sampling* is useful for capturing discrete events or circumstances; in this case, an event prompts an assessment.

If one was interested in how pain levels or flares were associated with unpleasant interactions at work, respondents could be instructed to complete a pain assessment whenever such interactions occur. *Hybrid sampling* schemes combine these and other sampling schedules to accomplish particular goals. Event assessment might be used to record when analgesics were taken and concurrent pain at that moment, which could be followed by a series of fixed-time assessments to track the pain response (as one might do in a laboratory experiment). Thoughtful and creative sampling of moments and events is a hallmark of EMA research.

The second topic is the length of the period queried in an EMA assessment. Asking about the moment just before a prompt eliminates retrospection and the associated bias. This is ideal for understanding immediate pain. However, one often has interest in relatively infrequently occurring daily events (eg, taking of medication) that are unlikely to be recorded with random sampling of immediate moments. The *coverage model* of momentary reporting (cEMA[33]) extends the reporting period to the last several hours or since the last time the individual was prompted (an extended period chosen by the researcher), so that much more of the day is sampled. The disadvantage of cEMA is that recollection of experiences even over relatively brief periods

can distort information (including how individuals choose to summarize pain over the period).[33]

Finally, we note that the content addressed in momentary studies to date has been diverse: it includes self-reports of a wide variety of inner states (eg, pain, stress, depression, anxiety, daydreaming, emotions, and loneliness), behaviors (eg, sleeping, eating, drinking, cigarette smoking, urination, medication, sex, social interactions, work activities, commuting, social media, and reading), symptoms (eg, aches, tingling, itching, headaches, muscle pain, coughing, shortness of breath, and nausea), and environments (eg, current place, inside/outside, temperature, air pollution, and time of day) and objective data including physiological states (eg, blood pressure, heart rate, and glucose levels), behavior (eg, activity level), and environment characteristics (eg, air quality and noise level). In some studies, both self-reports and objective measures are obtained allowing for a dynamic view of biopsychosocial processes.[43] Many of these constructs may be of interest to pain researchers and could be studied concurrently with momentary pain measures. Regarding momentary studies of pain, the construct that has been most studied is pain severity, which is consistent with severity being the central construct in traditional pain assessments for both research and clinical applications. However, to obtain a full understanding of the pain experience, we recommend that other facets of pain be assessed with momentary methods, including sensory characteristics, emotional responses to pain, catastrophizing, pain-related behavior, and the impact on physical and social function.

A large number of resources are available for readers who would like in-depth treatment of many of the topics covered in this topical review[1,2,33,43,44,51]; in this article, we review several issues about momentary studies that we think are especially relevant for pain researchers and clinicians.

3. How momentary studies can enhance our understanding of pain

Momentary studies have considerable potential for enhancing our understanding of pain, and **Table 2** presents a summary of the types of associations that can be investigated (Ref. 1), including associations that are unique to high-density EMA data.

An intriguing feature of EMA is that it encourages a perspective of pain as a dynamic phenomenon. Individuals certainly differ in how much pain they experience on average, yet it is less known that there are surprisingly large amounts of variability in those levels and that there are often systematic temporal patterns in pain (**Fig. 1**). Ecological Momentary Assessment enhances the ability to quantify, predict, and possibly influence the ebb and flow of pain; this has been viewed as a paradigm shift in pain research.[56]

For acute pain, a natural application is tracking dynamic changes in postsurgical pain within and across days with momentary assessments, as illustrated in a recent study.[49] This study analyzed momentary pain reports of over 8000 patients, which were recorded by medical staff every 4 hours on postoperative days 1 through 7 and documented in patients' electronic medical records. Using Markov Chain modeling, they were able to predict the course of pain states during postoperative recovery. In the future, Markov decision processes could be used to determine the choice of action at each time point (ie, at each step of the Markov Chain) that leads to the fastest recovery.

In chronic pain research, repeated momentary data provide the basis for creating numerous summary statistics to characterize variations of a patient's pain in daily life. Simple statistics such as the maximum or minimum weekly pain level, the proportion of moments a patient typically spends at high or at low pain levels on

a given day, or the SD (ie, magnitude of fluctuations) around a patient's average pain level are just a few examples.[45] Borrowing from statistical models in research on emotion regulation, novel summary statistics have been developed to capture a patient's pain variability from EMA, including the probability a patient experiences acute changes in pain[35,41] and the relative durability of pain at elevated vs lower levels.[42] Such summary statistics of symptom variability could enhance accurate classification of chronic pain conditions[18] and facilitate detection of effective treatments. Women with fibromyalgia have, for example, shown more variability in fatigue levels compared to women with rheumatoid arthritis and osteoarthritis, highlighting important differences between conditions.[57] Pain variability has also been shown to moderate treatment effects in several studies,[17,32,50] which may lead to tailored treatment approaches for patients with different pain patterns. Finally, reducing momentary pain exacerbations and effectively managing pain fluctuations represent key elements of psychosocial and some pharmacological treatments; therefore, pain variability may represent a valuable endpoint in clinical trials.[35,40,45]

These examples demonstrate some of the uses of momentary data in the pain field. We suspect that imaginative scientists and clinicians will generate many more provocative applications for investigating pain and a myriad of social and biological factors.

4. Recent pain Ecological Momentary Assessment studies

Through 2016, over 100 reports used momentary pain assessments as shown in a recent review.[33] To update that report, we searched for EMA studies over the past 5 years published in *PAIN* and in the *Journal of Pain*. Eleven original articles were found that reported results from 9 different projects (see Supplemental Table 1, available at http://links.lww.com/PAIN/B159).[6,7,9,15,19,28,38,42,49,55] All the studies were observational designs and most investigated pain intensity,[9,15,19,28,34,38,42,49,55] pain interference,[7,19,27] and pain behavior,[19] or examined relationships between pain and other domains (such as sleep[55] or social support[9]). One study took a more methodological approach investigating the feasibility of promising statistical models.[42] The flexibility of EMA designs for studies of pain is evident in these studies.

We can infer why investigators chose momentary methodologies for their studies. A focus on within-person associations was apparent in all the analyses performed, and pain experiences aggregated over individuals for between-person analyses were evident in a small number of studies. In a series of studies, Burns[7,8,19] investigated the interactions between married couples of whom one or both experienced chronic pain. This "within-couples" design allowed the authors to show that increases in pain catastrophizing of patients were positively associated with spouse reports of patient pain behavior in concurrent and lagged analyses. In lagged analyses, Mun[34] used a structural equation modeling framework to investigate whether morning pain catastrophizing and afternoon pain severity sequentially mediated the relationship between previous night nonrestorative sleep and end-of-day activity interference. It should be clear that addressing questions like these would not be possible without repeated, momentary assessment data.

5. Momentary assessment innovations

The ability to conduct real-time, momentary assessment in people's everyday lives informs our understanding of the pain

Applications of momentary data for pain research.

Application	Pain experience variables*	Research question examples
Summarizing pain experiences over time	Average pain intensity†,[6]	What is a participant's average pain level? What are the between-person differences in average pain level?
	Variability in pain intensity†,[35]	What is participant's variability of pain level? What are the between-person differences in variability of pain levels?
	Other summary measures (eg, maximum pain level, amount of time in pain, average pain after wake-up)†,[40]	What proportion of time did the participant experience pain? What was the participant's maximum pain over the day? How do participants differ in pain after waking up?
Modeling the effect of time on pain experience	Average starting level of pain†,[20]	What is the participant's level of pain at the beginning of the investigation (eg, at the beginning of the EMA monitoring period, week, or day)? How do patients differ in their level of pain at the beginning of the time scale under investigation (eg, at baseline in a clinical trial)?
	Rate of change in pain level†‡,[30,37]	How has the participant's pain level changed across the time scale under investigation (eg, over the course of the EMA monitoring period, over the week, or over the course of the day [ie, diurnal rhythm])?
Modeling within-person processes	Concurrent or lagged effects[29,34]	How does negative affect relate to pain levels and how does it predict changes in pain levels over time?
	Individual's dynamic change in pain state[42,49]	What is the short-term effect of a treatment decision on a patient's pain trajectory? How frequently does a patient oscillate between high and low pain states? How long does a specific pain state persist?

This table was adapted from the study by Bolger et al.[1]
* Example studies are cited.
† All these applications may be used to investigate within-person states and between-person differences.
‡ Primary application for EMA in clinical trials.
EMA, Ecological Momentary Assessment.

experience in new ways. Beyond this, though, has been the development of methods for using momentary assessments in innovative ways that may be of interest to the pain community. First, technology developed for capturing pain assessments can be harnessed to provide rapid feedback to clinicians about the status of their patients. Such technologies have already been implemented in other areas (eg, weight loss, anxiety, and diabetes management) and have the potential for enhancing
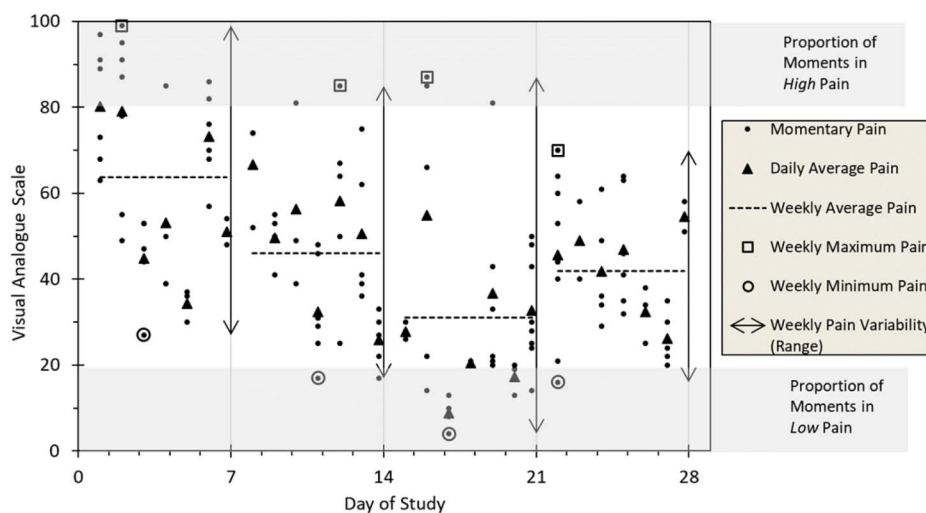

Figure 1. Variability in Pain Intensity and selected summary statistics that can be computed from EMA to characterize a patient's pain in daily life. X-axis ticks represent 28 sequential days of EMA monitoring for a single fibromyalgia patient. EMA, Ecological Momentary Assessment.

timely communication between patients and providers in the field of pain management, with the obvious goal of allowing quicker responses to changing clinical states.[23,52] In a framework of diverse clinical data (ie, laboratory results, apparatus-based findings, and medical records) and other monitoring devices (ie, activity or sleep tracker), EMA could be a promising add-on that might improve the prediction of individual pain states.[25]

A second promising development is the use of momentary, real-time information for directing immediate treatment paradigms, often using the same technology used for assessments. Ecological Momentary Interventions [23] and Just-In-Time Adaptive Interventions [36] are terms referring to smart systems that use momentary, real-time assessments to initiate and tailor interventions to each individual. These approaches are grounded in the idea that the right *kind* of treatment at the right *time* can enhance outcomes. As an example, momentary assessments of mood, stress, location, and activities could be used to forecast periods of susceptibility (eg, pain flares and exacerbations) to decide when to deliver momentary interventions. Alternatively, individuals' coping or activity patterns could be used to determine which type of intervention to deliver with Just-In-Time Adaptive Intervention. Although research on the development of these novel intervention methods is in its early stages, they hold considerable potential for pain management and research.

6. Conclusion

This brief review provided readers with an understanding of the rationale for Ecological Momentary Assessment, an overview of the mechanics of momentary assessment, showed how this methodology has been used in pain research, and discussed how it may be incorporated into future research and practice.

Conflict of interest statement

A.A. Stone is a senior scientist with the Gallup Organization and a consultant with Adelphi Values, Inc. The remaining authors have no conflicts of interest to declare.

Acknowledgments

Appendix A. Supplemental digital content

Supplemental digital content associated with this article can be found online at http://links.lww.com/PAIN/B159.

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