Analytical Sciences (2022) 38:71–83
https://doi.org/10.2116/analsci.21SAR11

REVIEW

Recent progress in the development of improved reference electrodes for electrochemistry

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Received: 30 September 2020 / Accepted: 26 November 2021

Abstract

A vital part of almost every experimental electrochemical set up is the reference electrode. As the development of working and indicator electrodes progresses to sensors with greater long-term stability and efficiency, it is important for reference electrodes to keep up with that progress. In this review, the deficiencies of commonly used reference electrodes are discussed, and recent work in the development of new reference electrode designs for more stable and reliable electrochemical experiments is highlighted. This encompasses work with salt-bridge reference electrodes comprising nanoporous and capillary junctions, solid-contact reference electrodes, and ionic liquid-based reference electrodes.

Keywords Reference electrodes · Salt bridges · Liquid junction · Ionic liquid reference electrodes · Solid-contact reference electrodes

Unmet challenges for the development of reference electrodes

Reference electrodes are an integral part of measurements with almost every electrochemical technique, including potentiometry, voltammetry, amperometry, impedance spectroscopy, and many others. As such, they are expected to provide a reproducible and stable half-cell potential in a wide variety of sample solutions and situations [1]. Ideally, a reference electrode will meet a number of important criteria, namely that it has a half-cell potential that exhibits no drift and only minimal temperature dependence without any hysteresis, obeys the Nernst equation with respect to a species comprised within the reference half-cell, undergoes only a vanishingly small half-cell potential change when a current is applied to the system, and is robust to poisoning by chemical species such as ammonia, hydrogen sulfide or strong bases that are present in some challenging samples [2].

In practice, it is difficult to find a reference electrode that meets all of these criteria, but some can come very close to this ideal, such as the commercially available double junction reference electrodes that work well in short-term experiments with comparatively large aqueous samples. However, the development over recent years of exceptional working and indicator electrodes with improved long-term stability, reproducibility, and compatibility with a wide range of samples has greatly benefitted challenging applications such as long-term monitoring with field-deployable, wearable, and implantable sensors. As a result, reference electrodes that used to be satisfactory in every respect no longer meet the requirements of demanding real-life applications, driving once again the development and study of reference electrodes. Notably, quality requirements for reference electrodes are particularly stringent in the case of potentiometry. In particular, the push for long-term monitoring with wearable and implantable potentiometric sensors results in an increasing need for reference electrodes that contribute with drifts of one microvolt per hour or less over periods of days and longer. Similarly, for many applications the desire for calibration-free potentiometric devices requires half-cell potentials to be reproducible to one millivolt or less [3].

Unfortunately, the original literature on reference electrodes often does not comment on many of these characteristics, and when it does, there is a noticeable lack of uniformity in reported characteristics, making it difficult to

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compare different types of reference electrodes. One recent publication highlights such shortcomings in the literature and included stability and drift data for a number of different reference electrodes designs with polymer-based reference membranes, although only for relatively short time points of 30 h. This study concluded that a polyurethane (with 25% tetrabutylammonium tetrabutylborate) membrane salt bridge had with < 1 µV/h over 30 h the lowest drift, with a standard deviation on the order of ± 30 µV. However, evidence of electrode lifetime and longer drift experiments of multiple days were not conducted [4].

This review highlights three commonly used types of reference electrodes; that is, liquid junction, solid state, and ionic liquid ones. It shows where currently available electrodes are coming close to realizing the strenuous requirements of demanding applications, and where they still have limitations with respect to long term stability, device-to-device reproducibility of the half-cell potential (E^o), independence of the half-cell potential from sample concentrations, suitability for complex samples, in vivo compatibility, and ease of operation.

Reference electrodes that require a liquid salt bridge

Reference electrodes typically belong to one of two categories of electrodes. Electrodes of the first kind involve a metal placed in contact with a reference solution containing the cation of the same metal, such as when a silver wire is placed in a solution of Ag^+ $\left(M|M^+\right)$ [5, 6]. Electrodes of the second kind include a metal that is in contact with a sparingly soluble, solid salt of the corresponding metal cation and are immersed in a reference solution of the anion forming that salt. The most common example is the Ag/AgCl system. One way to separate the reference solution from the sample solution is by use of a salt bridge, which must maintain electrical contact between the sample and the reference solution by ionic conductivity, while having a relatively small resistance [7]. In practice, salt bridges are commonly contained in porous glass or polymeric frits, hydrophilic gels, membranes, or capillaries, each with their own advantages and limitations.

Since reference electrodes comprising mercury have almost completely disappeared due to toxicity concerns, the most frequently used reference half-cell is the Ag/AgCl reference electrode. It consists of a silver substrate coated in silver chloride that is in contact with a concentrated chloride solution, typically 3 M KCl saturated with AgCl [2]. Ag/AgCl reference electrodes are popular due to their stability, low toxicity, and the small temperature dependence of their half-cell potential.

Limitations in reproducibility associated with Ag/AgCl components

Durability of Ag/AgCl components is essential for long term use of sensors. Limitations of the reference electrode lifetime can result from loss or damage to the AgCl layer, as it can result from either residual reductive currents—a problem particularly relevant for nanoelectrodes [8]—or frequent exchange of the chloride solution in contact with the AgCl layer, resulting in dissolution of the AgCl as a result of $AgCl_2^-$ formation [9].

The use of a polyimide layer to improve durability has shown interesting results. In this case, a gold backbone is coated with silver and subsequently hydrophobic polyimide layer. Lastly, AgCl is chemically grown on any remaining exposed silver in an $FeCl_3$ solution [10, 11]. This technique resulted in exceptional heat resistance up to 300 °C and good resistance to high Cl^- concentrations for 24 h resulting in drifts less than 1 mV over 24 h and a reproducibility of E^o of ± 0.88 mV. At the time of publication a drift of less than 1 mV over 24 h (< 42 µV/h) looked very desirable, but in view of recent reports of solid-contact ion-selective electrodes (ISEs) [12] with drifts on the order of 10 µV/h and lower [3], the drift no longer appears low enough. Given the one-digit nature of the drift value reported in the original literature, it is unclear how well performing those reference electrodes really were.

The quickest and simplest methods for fabricating Ag/AgCl elements in research laboratories involve either chemical or electrochemical coating of Ag substrates, such as wires, with AgCl, but this often results in bias potentials of ± 5 mV [5, 9]. In terms of E^o reproducibility, the variability and durability associated with these Ag/AgCl wires seems to be where improvements could be made for Ag/AgCl liquid junction reference electrodes. Other methods, such as the electrolytic and the thermal-electrolytic methods, require more time and steps, but prepare Ag/AgCl components with very small bias potentials (± 20 µV) [9]. With the thermal-electrolytic method, a spongy silver layer is deposited on a platinum support through thermal (500–600 °C) decomposition of a paste comprising silver oxide, which is then electrochemically converted to AgCl at the surface either by application of a fixed potential or a fixed current while the wire is submerged in a HCl solution [5, 13]. Interestingly, a recent study showed that for the thermal-electrolytic method, higher reproducibility was achieved using a fixed potential rather than a fixed current (± 9 µV versus ± 31 µV, respectively). [14].

Measuring very low drifts of reference electrodes is complicated by the fact that every potentiometric measurement involves two half cells, and attributing drift to one half cell only is impossible. In our own experience, the best, although not ideal, method to assess the quality of a reference electrode is to measure its potential relative to a well-conditioned Ag/AgCl electrode immersed into a KCl solution, keeping the temperature constant, preventing evaporation, and shielding the electrochemical cell from light.

Benefits and disadvantages of free-flowing liquid salt bridges

The use of well-defined liquid salt bridges and knowledge of their effect on the stability of reference potentials is critical to stable and reproducible electrochemical measurements. Flow of the inner filling solution into the sample solution creates ionic contact with the sample and avoids contamination of the reference electrode with sample components [2], but there are drawbacks to consider too. In the case of so-called free-flowing liquid salt bridge reference electrodes, the flow of electrolyte out of the reference electrode is of a moderate level, providing high stability, minimal stirring effects, and minimal electrode contamination in short-term experiments [15, 16].

For long-term experiments however, these electrodes are not ideal. Their flow rate can lead to contamination of the sample solution with reference electrode inner filling solution or—in the case of free-flowing double-junction reference electrodes [15]—bridge electrolyte, and they need to be refilled every couple of days. For reasons that are not fully understood but are likely related to instabilities in the flow profiles in the sleeve junction, the potential of such reference electrodes often transiently fluctuates by a few millivolts upon refilling of the bridge electrolyte or reference solution reservoir. Carefully avoiding such complications, the relative drift of free-flowing double-junction reference electrodes with a sleeve junction providing contact to the sample has been shown to be as low as 7.5 µV/h over 80 h, as determined by measuring two such electrodes relative to one another [17].

Flow-restricted liquid salt bridges

To address the sample contamination problem and reduce the frequency of refilling, free-flowing reference electrodes with greater flow restriction have been employed [18]. While the use of ceramic frits is very common in combination pH glass electrodes (i.e., electrodes in which the reference and sensing electrode are built into one single device), the bridge electrolyte compartment is typically sealed from the environment except for the frit junction, preventing net flow of solution through the frit. Only little has been published on the properties of ceramic frits suitable for use in reference electrodes, but pore sizes in the range of 0.3–3.0 µm appear to be most common, and flow rates of 0.2–25 µL/h have been reported for an experimental setup with gravity driven flow [19].

The use of nanoporous frit-based flow restriction is also quite common, especially in research laboratories. Frit materials can vary, from glass (available under brand names such as CoralPor, Electro-porous KT, and Vycor) to polymeric materials (such as polyethylene or Teflon). Reference electrodes with nanoporous glass frits in particular have been used frequently in many types of electrochemical experiments for several decades [20], but only in 2013 were the limitations of these devices discussed systematically [18, 21]. Notably, the small pore sizes (commonly 4–10 nm pores with ~ 4 µL/h flow rates) used in frit-based liquid salt bridges can lead to charge screening, resulting in electrostatic forces acting on electrolyte ions caused by negatively charged surface groups on the glass surface. This ultimately can lead to unexpected deviations in the half cell potential

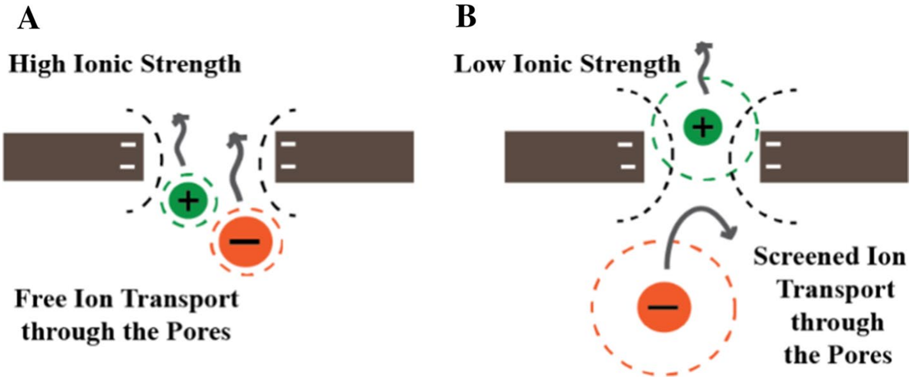

Fig. 1 Two-dimensional representation of a pore in a porous glass network. The rectangles represent the glass structure, negative signs show the surface charge density on the pore walls, and the dashed lines represent the Debye length. In a sample with high ionic strength, the Debye length is smaller than the diameter of the pores, and ion transport occurs freely through the pores (**A**). In a sample with low ionic strength, the Debye length is larger than the pore diameter, and ion transport is impacted by electrostatic forces (**B**). Reproduced with permission from reference [16]

of the reference electrode, as shown in Fig. 1 [18, 21]. This is especially apparent in low ionic strength solutions, and it can also lead to potential fluctuations when samples flow by the liquid junction with variable speeds, such as when the samples are stirred at an uneven rate.

To avoid sample-dependent liquid junctions at nanoporous frits, pore sizes less than 10 nm are recommended only for high ionic strength samples (where Debye lengths are smaller), while pores in the range of 1 µm are more suitable for low ionic strength solutions [22]. The latter do result in higher flow rates, though, and that can result in sample contamination when either very small samples are used or measurements are performed over longer periods of time.

Alternatively, polymeric frit materials, such as Teflon and polyethylene, reduce the effects of charge screening due to their lack of ionic surface groups and relatively large pore sizes. Unfortunately, their larger pore sizes (~ 10 µm for polyethylene and ~ 1 µm for Teflon) result in relatively large flow rates and their hydrophobicity makes wetting of these frits difficult, leading to high electrical resistances [18]. To alleviate these effects, mesoporous polymer frits with pore sizes of ~ 10 nm and electrically neutral hydrophilic pore walls for easy wetting were developed. These frits maintained a low flow rate (0.007 ± 0.003 µL/h) and exhibited no hysteresis effects while decreasing the charge screening effect in low ionic strength solutions by a factor of 3 [23].

While restricting the volumetric flow is generally desirable for reference electrodes, especially in long-term measurements, restricting the flow of bridge electrolyte through a frit junction too much can result in contamination of the bridge electrolyte, as shown in Fig. 2. In this example, after just 5 min, diffusion of SCN^- from the sample solution into frits filled with $FeCl_3$ solutions of higher concentration is evidenced by the appearance of a red color resulting from the formation of the complex $Fe[(SCN)(H_2O)_5]^{2+}$. When sample components diffuse faster into the frit than the salt bridge flows out into the sample, unwanted deviations in the measured potential result [24]. Conversely, for frits comprising a low concentration of $FeCl_3$, no color change is seen, indicating that a low ionic strength results in partial charge screening, preventing the direct contact of SCN^- and Fe^{3+}.

It follows that a salt bridge contained in a capillary is generally preferable to a salt bridge contained in a frit. The high linear flow rate of the capillary minimizes contamination of the salt bridge by diffusion of sample components into the salt bridge, and the low volumetric flow rate of the capillary is preferable to use of a frit-based junction as its low volumetric flow rate minimizes contamination of the sample with bridge electrolyte and reduces the frequency with which the bridge electrolyte needs to be refilled.

Liquid salt bridge reference electrodes for improved drift and stability

An alternative approach to reduce the total flow of the bridge electrolyte is the use of timed flow. Higuchi et al. developed a miniaturized Ag/AgCl reference electrode based on a valve actuator for measurements of pH in cow rumen. This valve allows for an intermittent electrolyte flow for about 5 s once per hour, resulting in an overall flow of about 0.002 µL/h. This suggests a reference electrode life of over 2 years [25]. Unfortunately, miniaturized single-junction Ag/AgCl electrodes suffer from dissolution of the AgCl into the inner filling solution, resulting in larger long-term drifts, in this case 0.47 mV over 24 h (~ 20 µV/h). To address this challenge, a voltage was applied to an integrated platinum electrode to generate in situ hydrogen pressure and simultaneously rejuvenate the AgCl/Ag element by coating it with AgCl [26, 27]. This led to a reduction in drift to ~ 10 µV/h, but also resulted in a larger flow rate of 1 µL/h. Longer-term measurements will still be needed to ensure the electrodes indeed perform as well for such long periods of time. Ultimately, while the drift and life-expectancy of these valve actuator sensors may work very well for this particular application,

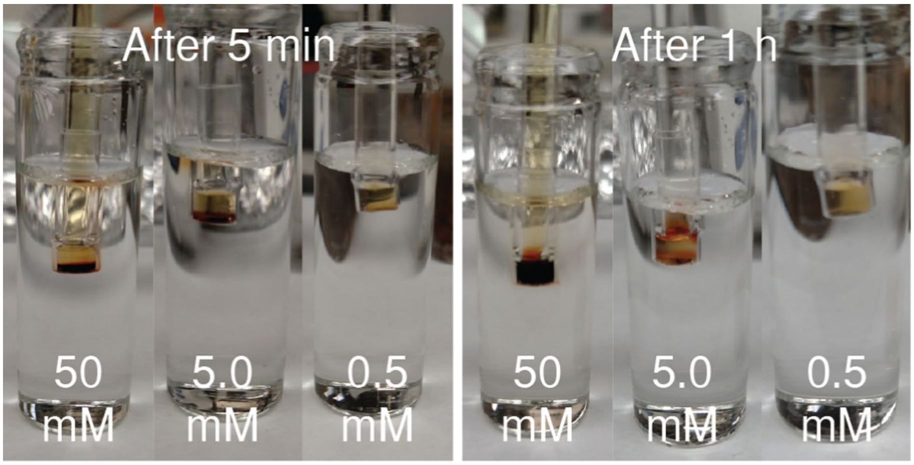

Fig. 2 Images of reference electrodes filled with $FeCl_3$ in contact with unstirred sample solutions of 2.5 M KSCN/1.0 M KCl. The $FeCl_3$ concentrations and times of immersion of the reference electrodes into the sample solutions are indicated in the individual panels. Figure adapted with permission from reference [22]

an improvement in overall drift is still necessary for other uses.

Quite recently the use of applied pressure to drive electrolyte flow through a capillary-based liquid junction was used for the development of an inexpensive Ag/AgCl reference electrode. In this case, flow through a 5 cm long capillary of 10.2 μm diameter resulted in a stable salt bridge leading to rather minimal drifts of 6 ± 3 μV/h versus a Ag/AgCl wire in a KCl solution over 21 days [28]. This demonstrates a much longer continuous measurement of drift for a reference electrode than typically observed, and due to the small volumetric flow of electrolyte, refilling is not needed in that time frame. The use of a capillary also alleviates the sample dependent potential differences and stir rate dependence observed with some nanoporous glass frit junctions, while ensuring that the capillary does not become contaminated by sample components. This is not the first example of a pressure driven flow through a capillary salt-bridge, but its drift is one of the best reported. The resistance of this type of electrode is in the range of 30 MΩ, which as a result of the small cross sectional area of the capillary is larger than for many other often used electrodes, but is of the same order of magnitude as for a pH glass electrode and is compatible with most modern voltmeters.

Another method for creating a low-flow reference electrode involves the use of pressure-driven flow through a glass plate with an array of nanosized holes, which conceptually is equivalent to a bundle of capillaries. An electrode of this type with 157 nanochannels of 500 nm diameter was developed for use in pH measurements and demonstrated a flow of 360 ± 60 nL/h and a drift of -0.013 pH units over 6 months, while also exhibiting no change in potential with stirring and exceptional stability in extreme pH and low ionic strength solutions [29]. The nanochannels were 500 nm diameter wide, which is large enough to eliminate electrostatic screening. The resistance of these reference electrodes was reported to be smaller than 1 MΩ. As the combined cross section of the 157 nanochannels was 31 μm^2, which is relatively close to the 81 μm^2 for a single 10.2 μm capillary, the lower resistance as compared to the 10.2 μm capillary device described above is largely due to the shortness of the nanochannels, which we estimate based on the conductivity reported in the original literature to be approximately 1 mm.

Evidently, liquid junctions with single but shorter capillaries could be prepared, reducing the difference in electrical resistance between single capillary junctions and nanochannel array junctions but increasing the flow rate in the capillary, which is inversely proportional to the capillary length. The key advantage of a nanochannel array is arguably that the flow rate is proportional to the channel radius raised to the fourth power, reducing the flow rate of a channel array significantly as compared to the flow rate through a single capillary of equal channel length and the same cross sectional area as the channel array. However, at this time, fabrication of an array of channels of very small dimensions is more challenging and pricier than use of capillaries, which can be prepared readily and are commercially available at low cost.

Flowless salt bridges

Many commercial reference electrodes comprise a gelled salt bridge that eliminates any flow of electrolyte from the reference electrode into the sample [30]. A similar setup was also chosen for a microneedle-type Ag/AgCl reference electrode with an agar gel based salt bridge [31]. In this case, a rather small potential deviation of ± 0.33 mV was observed over 7 days, very promising for long term experiments, but quantitative data for reproducibility and device-to-device performance was not reported. Unfortunately, the use of gelled salt bridges often leads to unwanted limitations such as increased long-term drifts and biofouling [32]. Many inexperienced users of glass pH combination electrodes have complained about the slow response of their pH sensors when in reality the response time of their sensor system was limited by a flowless salt bridge either depleted of electrolyte or contaminated by prior samples.

A recent intriguing development in flowless reference electrodes utilizes a so-called leakless, bipolar electrode consisting of a platinum wire (sealed to eliminate leaking) placed in contact between the sample solution and the reference electrodes inner filling solution. While drifts of only about 2 μV/30 min were reported for potentiometric experiments, the lifetime of these reference electrodes is still quite short, and drifts unexplainably increased for voltammetric experiments [33]. The response mechanism of so-called leakless bipolar reference electrodes is also unclear at this time, suggesting that more research has to be performed to make this approach viable for routine measurements.

Solid-contact reference electrodes

The increasing popularity of solid-contact ion-selective electrodes, where a solid-state material is used to replace the typically large-volume inner filling solution of conventional reference electrodes, has also interest in the development of reference electrodes with a similar construction. Many of these reference electrodes are constructed in a manner analogous to solid-contact ISEs and comprise a solid-state ion-to-electron transducer in contact with the underlying electron conductor.

A range of solid-contact reference electrodes with little interference from common sample ions and redox-active interferents, including oxygen (which is particularly relevant for solid contacts comprising conducting polymers), have been developed. However, there has been only a limited effort to assess the lifetime of such electrodes when exposed to complex samples such as body fluids or food samples. Several studies have produced reference electrodes with a high initial device-to-device reproducibility on the order of ± 1.0 mV. However, they often have other drawbacks, such as a high subsequent emf drift or, as for reference electrodes based on solid KCl melts, long initial conditioning times. For example, two reports of reference electrodes with poly(vinyl acetate) [34, 35] films containing solid KCl showed stable emf values within a few mV over periods of up to several months. While one of these reports described electrodes [34] with a high device-to-device reproducibility, an assessment of electrolyte stability was not performed. The other report described electrodes [35] with a slow response time in some solutions. Reference electrodes with polymeric films comprising AgBr were easy to prepare and showed a high reproducibility, with a low drift over the time period studied, but lifetime studies were limited to 10 days, UV sensitivity was not assessed, and slow response times were observed in some solutions [36].

The number of relevant criteria to characterize solid-contact reference electrodes is rather high, and which ones are relevant depends on the type of real-life application considered. This can make it difficult to compare different approaches. In the following, we give an overview of different types of solid-contact reference electrodes, with a particular emphasis on where different approaches excel. Documented weaknesses or characteristics that have not been reported are also highlighted, but it must be noted that apparent drawbacks of this type are not relevant for all types of applications. For example, long term stability is hardly relevant for single-use devices, and device-to-device reproducibility is not important for an application that requires calibration of the sensing electrode. The discussion here does not address the literature comprehensively, but highlights reports on solid-contact reference electrodes that appear particularly suitable for practical applications, have provided special insight to developers of such electrodes, or are based on an approach that has promise to excel upon further refinement.

One method for constructing solid-contact reference electrodes is to define the phase boundary potential at the interface to the sample using a polymeric membrane doped with an ionic liquid, as discussed also in Sect. Ionic liquid reference electrodes, or a relatively hydrophobic salt that can partition across the membrane/water interface [37–41], as described here. The solid transducing materials between these membranes and the underlying electron conductor are typically the same as those used for ISEs, such as large surface area carbon materials, conducting polymers, or redox-active compounds. Alternatively, solid-contact reference electrodes have been developed using a hydrophilic salt that slowly dissolves into the sample [34, 35, 42–44]. The backside contact is typically Ag/AgCl. Additionally, there are several examples of polymeric membranes doped with chloride salts deposited directly onto a Ag/AgCl contact [36, 45–52], and examples of reference electrodes combining several of these approaches. Figure 3 shows schematics for some common device configurations. Because the function of all these solid-contact reference electrodes is inherently depending on the continuous dissolution of a salt into the sample, their lifetime is finite and limited by the size of the electrolyte reservoir, a drawback that they share with classical free-flowing liquid junction reference electrodes, which require regular refilling of the electrolyte solution. Some solid-state reference electrodes mitigate this problem by incorporating large amounts of solid electrolyte or a design that ensures dissolution of this solid is as slow as possible.

Solid-contact reference electrodes containing hydrophobic salts

Although many investigations of membrane-based reference electrodes have used ionic liquids (Sect. Ionic liquid reference electrodes) as a hydrophobic salt to define the phase boundary potential, several alternative configurations with other hydrophobic salts have been tested. It was attempted to develop a reference electrode based on a poly(pyrrole) (PPy)

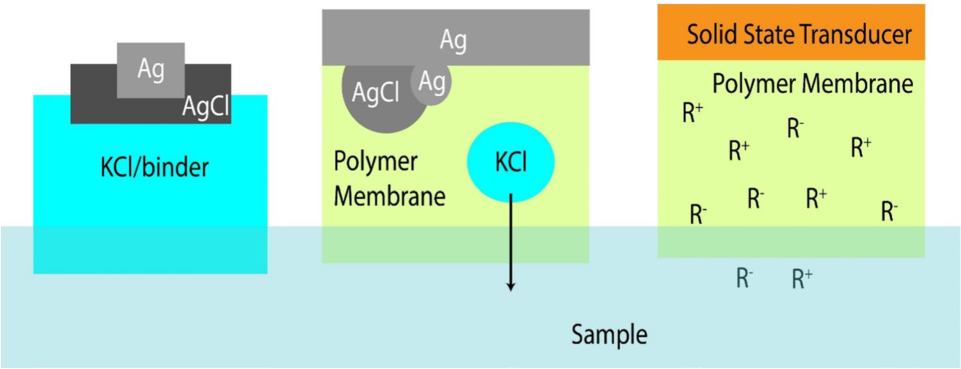

Fig. 3 Schematics for three configurations of solid-state reference electrodes: Solid KCl, sometimes containing a binder material (left); Ag, AgCl, and KCl dispersed within a membrane (center); and membranes containing a hydrophobic salt that partitions into the sample (right)

membrane doped with a variety of anions. Doping with perchlorate and dodecylbenzenesulfonate in a 6:4 ratio resulted in the best performance, with a − 0.3 mV/decade slope in response to KCl. Although these electrodes are sensitive to redox-active interferents, when covered with a PVC membrane containing Ag/AgCl/KCl as well as both a cation and an anion exchanger, very low electrolyte dependence of less than 1.4 mV/decade for Na^+, K^+, Cl^-, NO_3^+ was observed, along with no pH or redox sensitivity [39]. Similarly, poly(3,4-ethylenedioxythiophene) doped with poly(styrene sulfonate) (PEDOT(PSS)) covered by a PVC/DOS membrane containing both a cation and an anion exchanger was tested as a reference electrode, which showed fair stability to Na^+, K^+, Ca^{2+}, Cl^-, CO_3^{2+}/HCO_3^+, and pH, though only limited characterization was reported [40]. Devices with several layers consisting of multi-walled carbon nanotubes, a tubular-like Au-tetrathiafulvalene^0/tetrathiafulvalene$^+$ crystal, and a plasticized PVC membrane containing both a cation and anion exchanger showed a less than 2 mV/decade slope for Mg^{2+}, Ca^{2+}, Li^+, NH_4^+, no effect of pH, gas, or redox-active compounds, and a 0.208 mV/h drift. In an integrated paper-based format, the standard deviation was within 1 mV, with a drift as low as 0.02 mV/h over 27 h. The device-to-device reproducibility of $E°$ was ± 4.6 mV with an $E°$ change of only ~ 5 mV over two months of storage. [41].

Solid-contact reference electrodes with a solid KCl reservoir

Several different approaches have been studied that use a solid KCl electrolyte reservoir, often mixed with non-plasticized PVC or another inflexible polymer as a binder, which is in contact with a AgCl coated Ag wire. An early example is a solidified KCl melt surrounding a Ag/AgCl element held together in a ceramic body, which can be combined with a small amount of another salt at the sample interface as a bridge electrolyte. These electrodes were as stable as a 1 mV potential change over 3 months, although they unfortunately had a response time of a few minutes. They could also be autoclaved [42]. A KCl/PVC composite material that can be 3D-printed, comprising 50% KCl, 32.5% PVC, 1.5% Ca/Zn, and 16% diethylhexyl terephthalate, has also been used as a reference electrode. Using a Ag/AgCl contact, the standard deviation of potential value was ± 10 mV from device to device, and the potential was stable over 3 months. No effect from carbon dioxide, oxygen, KBr or KSCN was observed, and there was no pH sensitivity. [43].

Poly(vinyl acetate) has been used as a matrix to hold electrolytes in solid state reference electrodes. A method using a crosslinked vinyl acetate as matrix for KCl was investigated, using a Ag/AgCl wire suspended in a monomer solution with KCl, followed by polymerization. Initial conditioning required 3.6 to 8.3 days, depending on the degree of crosslinking. The electrode-to-electrode standard deviation was on the order of ± 1 mV, noise was less than 1 mV, and the range of potential response was less than 7 mV. After 180 days, the potential was still within 5 mV of the original value. In 1 M KOH, the working time was about 9 days, while in 1.02 M H_2SO_4, the working time was at least 65 days. The maximum drift was 1.0 mV/day [34]. Poly(vinyl acetate) powder mixed with vinyl acetate monomer and KCl was polymerized on exposure to UV light to produce solid-state reference electrodes. Although these required 3 days of conditioning, they were stable within ± 5 mV over at least 2 months. An electrode with a LiOAc portion of the composite material at the bottom to create a "double-junction" style reference electrode was also fabricated. Solutions of K^+, Na^+, Cl^-, Br^-, HCO_3^-, and H^+ resulted in a potential within ± 1 mV, although exposure to some solutions led to transient emf spikes followed by a return to the prior emf over the course of several minutes. These reference electrodes could be used in chloride measurements, as the chloride leakage from the electrode was slow enough that no interference was observed. The chloride leakage was also assessed by measuring the conductivity of deionized water into which the reference electrode was immersed. After one hour, the conductivity was 47 µS, while it was 160 µS in the corresponding experiment with a 3 M KCl single-junction reference electrode [35]. In a follow-up, this composite reference electrode was used with a conducting polymer-backed solid-contact ISE incorporated into the body of the reference electrode. In river water containing a high amount of sediment, the composite reference electrode worked better than a commercial single junction 3 M KCl reference electrode, which is believed to be the result of a liquid junction that is less easily clogged. [53].

Somewhat similarly, injection molding was used to fabricate a solid-state reference electrode using a mixture of KCl and poly(vinyl acetate) molded around a Ag/AgCl wire. The best stability was observed with high KCl concentrations in solution, and after 71 days of storage in 3 M KCl, no drift greater than ± 0.2 mV over 10 min was observed, but in 0.1 M KCl, drifts of this magnitude appeared after 29 days. Storing in humid air resulted in no need for reconditioning. Almost no response was observed to K^+, Cl^-, Na^+, Br^-, HCO_3^-, H^+, but a potential change of several mV was observed on exposure to OH^-. The salt leakage from this reference electrode was shown to be much lower than that from a commercial reference electrode by measuring the conductivity increase of deionized water. After the reference electrodes were immersed for one hour, the conductivity was 1.5 µS for the poly(vinyl acetate) reference electrode and 158 µS for the commercial reference electrode [44].

Solid-contact reference electrodes with Ag/AgCl/KCl dispersed in a membrane

Many configurations have been used to develop reference electrodes using AgCl/Ag particles and KCl dispersed within the membrane, either with or without another transduction material such as high surface area carbon or a conducting polymer. Membranes composed of crosslinked butylacrylate, containing AgCl, traces of Ag, KCl, and the hydrophobic electrolyte salt ETH500 were used with a PPy layer doped with chloride. Although these electrodes had a relatively high drift of 1.5 mV/h over 5 h, there was no effect on the reference half-cell potential from Na^+, K^+, Cl^-, and NO_3^-, only a small effect from oxygen, and no effect of other redox interferents in solution, a slope less than 0.1 mV/pH unit between pH 2 and 12, but a greater than 10 mV change in potential on exposure to a 1 mM cationic surfactant [45]. Solid-state reference electrodes have also been prepared in an analogous manner with AgBr. Compared to AgCl, AgBr has the advantage of a lower solubility in water, but the disadvantage of a higher UV sensitivity. Suspensions of a 1:5 ratio of AgBr to KBr in a PVC/DOS membrane were drop-cast onto gold or glassy carbon electrodes either with or without a layer of silver electrodeposited on the surface. Some silver was formed in the salt mixture by several methods. Exposure to UV light to produce Ag metal on a Ag substrate resulted in the lowest standard deviation of device-to-device potentials at ± 1.09 mV. Potentials were stable within ± 2 mV over 10 days. No effect of bromide was observed up to 1 M and there was no response to Li^+, K^+, Na^+, Ca^{2+}, Cl^-, NO_3^-, HCO_3^-, pH, almost no effect of oxygen, and no effect from other redox-active species [36].

Polyacrylic membranes were studied with carboxylated single-walled carbon nanotubes to increase capacitance of the electrode surface, with AgCl, Ag, KCl, and ETH500 included in the membrane. After a necessary 24-h conditioning, the drift was − 1.1 mV/h over 12 h for the best-performing photopolymerized butylacrylate membranes. K^+, Na^+, Cl^-, NO_3^- resulted in at most a 1.0 mV/decade slope, while pH and light had extremely small effects on the response. The Ag/AgCl in the membrane was required to observe high stability [47]. Butylacrylate membranes have been developed using microspheres composed of crosslinked butylacrylate and comprising KCl and AgCl with traces of Ag. The microspheres were prepared and mixed into a solution of butylacrylate and ETH500, followed by polymerization of the bulk membrane on a poly(3-octylthiophene) (POT) layer. Without microspheres, the reference electrodes resulted in potential changes on the order of 20 mV when switching from KCl to NaCl, but K^+, Na^+, Cl^-, and NO_3^- had very small effects when microspheres were included. The microspheres are thought to slow dissolution of the electrolyte and result in well-dispersed electrolyte and Ag/AgCl, therefore reducing drift [48]. Several combinations of membrane components were tested with microvessels made of PPy that contained either KCl or AgCl, which were mixed into PVC/DOS membranes containing a cation and an anion exchanger and cast onto electrodes both with and without a POT layer. The best performance was observed without POT using PPy/AgCl vessels and KCl dispersed in the membrane. The standard deviation of measurements with the same device was within 1 mV on the same day, and the standard deviation of potential was within 4 mV over 1 month. The high reproducibility and stability was attributed to the formation of well-dispersed silver nanoparticles on the outside of these microspheres [49].

An alternative membrane material that has been used is poly(vinyl butyral), which has been used in several types of reference electrodes. In one case, two underlying transducers were tested: a Ag/AgCl contact covered with KCl and a poly (vinyl butyral) (PVB) membrane containing NaCl, the other a RuO_2 substrate covered with SiO_2 and a PVB membrane containing SiO_2. A low sensitivity to pH and KCl was claimed, though for the Ag contact electrode, a 5.2 mV/decade slope for KCl was observed. The Ag/AgCl electrode also had a high drift in the pH-ISE setup of 31 mV/h, while the drift was only 2.2 mV/h for the RuO_2/SiO_2/PVB reference electrode [51]. A PVB membrane with colloidal AgCl and NaCl, which was exposed to UV light to generate Ag metal was also used. The electrodes were stable after 12 h of conditioning, with a 0.2 mV/decade response to KCl, with a drift of 90 μV/h over 14 h. These reference electrodes were tested against Li^+, NH_4^+, Mg^{2+}, Na^+, Cl^-, SO_2^{2-}, HCO_3^-, pyruvate, urea, albumin, glucose, and acetate, for each of which a less than 1.0 mV change per tenfold increase in concentration observed below 0.1 M. These electrodes were also stable to pH changes between pH 4 and 10 and displayed no redox or light sensitivity. Atomic force microscopy, infrared spectroscopy, and electrochemical impedance spectroscopy were used to show that when AgCl and NaCl are included in the PVB membrane, significant changes take place after conditioning, including formation of nanopores in the membrane and a decrease of the resistance. A shelf life of 3 months of dry storage was demonstrated, after which the electrode could be reconditioned and perform well [52].

An easily manufactured solid reference electrode was prepared using a Ag/AgCl paste covered by a commercially available screen-printable, UV-curable, hydrophobic dielectric polymer (product 5018 from DuPont) blended with KCl particles. With Ag/AgCl paste sandwiched between two layers of the KCl-doped dielectric, the reference electrode had a lifetime of around 10 days and exhibited a drift of about 0.2 mV/h [54]. Planar reference electrodes were prepared on a PET substrate printed with Ag ink with a AgCl layer, covered by a membrane of a UV-curable ink (EMD 6200) containing KCl and the hydrophobic electrolyte

ETH500. Slopes of less than 1.0 mV/decade were observed in response to Na^+, K^+, Ca^{2+}, Cl^-, Br^-, NO_3^-, F^-, oxygen, redox species, or surfactants. While the pH stability was good between pH 3 and 9, outside of this range, the response was affected. The drift was 0.21 mV/h over 48 h, and device-to-device reproducibility was less than ± 1.0 mV. Scanning electron microscopy showed that when salts are added to the polymer, the conditioning process involves formation of micropores, lowering the resistance. The shelf life of these electrodes was at least 4 weeks [50].

Ionic liquid reference electrodes

Ionic liquids offer a viable alternative to conventional salt bridges and have recently attracted considerable attention [55]. In the early 2000s, Kakiuchi and co-workers reported the first systematic studies of the phase boundary potential at the interface between ionic liquids and aqueous electrolyte solutions [55]. After either a pure ionic liquid or an ionic liquid doped polymeric membrane is brought in contact with an aqueous sample, the ionic liquid transfers to some extent into the aqueous sample phase, resulting in equilibrium distribution of the ionic liquid across the interface of this two-phase system. Other ions present in the aqueous sample will not affect the interfacial phase boundary as long as they do not transfer to a substantial concentration into the ionic liquid phase [56]. Subsequently, Kakiuchi and co-workers investigated the properties of a wide range of ionic liquid-based reference electrodes against the silver halide reference electrode, demonstrating that they provide stable and concentration independent half-cell potentials. For instance, the phase-boundary potential between an ionic liquid mixture of heptadecafluorodecyl trioctyl phosphonium tetrakis[3,5-bis(trifluoromethyl)phenyl]borate and pentyltripropyl ammonium bis(pentafluoroethanesulfonyl) amide when used to measure in 0.5 M KCl solution deviated by 0.3 mV at most from the average over 1 h [57–59]. While this variability of the emf over time seems low for many other applications, it is comparatively high in view of long term measurements without recalibration. It appears likely that these reference electrodes could perform much better under more optimized conditions, but that was not the purpose of much of the early work with such reference electrodes.

Benefits and limitations to ionic liquid based reference electrodes

Compared to conventional salt bridges, there are several benefits of an ionic liquid-based salt bridge. A number of deficiencies of conventional salt bridges can be avoided, including the need to replenish the bridge electrolyte, fluctuations of the liquid junction potential resulting from contamination of the bridge electrolyte with sample components and insufficient or inconsistent flow of bridge electrolyte into the sample, as well as (in the case of low ionic strength sample) sample and stirring dependence due to electrostatic screening (see Sects. Benefits and disadvantages of free-flowing liquid salt bridges and Flow-restricted liquid salt bridges) [15, 60, 61]. Moreover, physical constraints for the junctions, as provided, e.g., by porous ceramics or glass, are not needed to separate inner reference and sample solutions. Instead, the physical robustness of the ionic liquid phase can be increased by incorporation of the ionic liquid into polymeric support membranes [62–64]. Polymers that have been used for this purpose include plasticized PVC [61–63, 65, 66], PMMA [67, 68], acrylate polymers [69], fluoropolymer [70, 71], and silicones [72] that offer greater mechanical strength and durability.

Due to the similarities between ion-selective and reference electrode membrane fabrication processes, incorporation of ionic liquids in a PVC matrix is of appeal, regardless of whether the matrix is plasticized or plasticizer-free. However, if a plasticizer is used, it can progressively leach out into the sample. This not desirable in the case of implantable sensors, as many plasticizers are endocrine disruptors and can trigger inflammatory reactions [73]. To that end, ionic liquid based reference electrodes with ionic liquid doped biocompatible silicones were developed [72], suitable for use in the range of electrolyte concentrations characteristic for human blood.

The use of ionic liquid reference electrodes does have its disadvantages too, though. When an ionic liquid reference electrode is used along with polymeric membrane ISEs as sensors for the analyte, leaching of the ionic liquid ions from the membrane into the sample solution may result in the ISE being exposed to these hydrophobic components [61]. This has been shown both for cation- and anion-selective ISEs [61]. Whether this effect does occur depends on the volume of the sample [60], the distance between the ISE and the reference electrode, and whether there is a flow of solution between the two. Moreover, interference of the ionic liquid with the ISE response is a concern if the selectivity of the ISE for its target ion is low with respect to the ionic liquid ion with the same charge sign as the target ion. Evidently, this limitation of ionic liquid based reference electrodes has its close analogue in the contamination of samples with the bridge electrolyte of conventional reference electrodes, which is why many researchers working, e.g., with K^+ selective ISEs will use lithium acetate rather than KCl as bridge electrolyte if they use conventional salt bridges. The difference between the two types of reference electrodes is that in the case of the ionic liquid reference electrode, the response of the ISE to the ionic liquid ion is typically unrelated to the ionophore. On the other hand, in the case of the conventional salt bridge comprising hydrophilic ions, the response of the ISE is more likely the consequence of ionophore-assisted transfer of salt bridge ions into the ISE membrane. Indeed, this type of sample contamination from conventional salt bridges has led Kakiuchi and co-workers to conclude that ionic liquid-based reference electrodes are particularly suitable for measurements in low ionic strength samples such as rain water [57, 74, 75]. Further, this type of reference electrodes has a limitation in applications that require standard phthalate solutions for pH calibration. It has been observed that the hydrogen phthalate ion interferes with the phase boundary across the ionic liquid and phthalate buffer interface, which not only affects the reliability of the pH measurement but also the lifetime of the ionic liquid reference electrodes [76]. Thus, phthalate ions should be be used with caution when utilizing ionic liquid reference electrodes for potentiometric pH measurements.

Another limitation of ionic liquid based reference electrodes results from the transfer of sample ions into the ionic liquid phase. Depending on the ionic composition of samples, this may either be an ion exchange, with a sample ion transferring into the ionic liquid phase in exchange for an ionic liquid ion of the same charge transferring into the sample. It may also be co-extraction, where a sample ion transfers along with an ionic liquid ion of opposite charge sign from the sample into the ionic liquid phase. When the concentration of sample ions is high enough, these two processes occur to an extent that the phase-boundary potential established by the ionic liquid is affected [62, 77]. Here too, there is an analogy to conventional salt bridges, which exhibit a liquid–liquid junction potential at the sample interface that also depends on the sample composition when samples contain very high ion concentrations. The difference here is that in the case of conventional salt bridges ions with high mobilities are most likely to affect the liquid–liquid junction potential, while for ionic liquid reference electrodes, hydrophilic sample ions are typically of low concern. A notable exception though is the hydrogen ion, which was shown to transfer with the ionic liquid anion bis(trifluorosulfonyl)imide into the ionic liquid phase, where the two ions associate to form an electrically neutral species [62]. This results in the failure of the respective reference electrodes at low pH.

There is indeed no one-size-fits-all approach. As for a conventional salt bridge too, when ionic liquid-based reference electrodes are used, the type of sample needs to be taken into account. While these principles all appear straightforward, more quantitative guidelines that would allow users to determine the ideal ionic liquid for a specific application have not been reported to date. Specifically, one should expect such guidelines also to predict how the use of a specific ionic liquid affects the upper concentration of sample ions for which the reference electrode half-cell potential is no longer independent of the ionic composition of the measured sample. In any case, researchers working with new ionic liquid membrane reference electrodes are strongly encouraged to report experimentally determined concentrations of sample ions at which the reference half-cell potential starts to depend on the sample composition.

Important characteristics of ionic liquid reference electrodes

The number of studies that have determined long term stabilities of ionic liquid reference electrodes is still relatively small. Reference electrodes with three-dimensionally ordered macroporous carbon as transducer that were coated with plasticized PVC membranes doped with an ionic liquid exhibited an emf drift of 0.042 mV/h over 26 days in 0.1 M NaCl solutions [62], and for a similar setup with CIM carbon and a redox buffer as the solid contact 1.7 µV/h drift over a 110 h was observed [63]. For measurements in tenfold diluted animal serum using a biocompatible silicone matrix doped with an ionic liquid, a drift of 112 µV/h over 5.8 days was found [72].

Similarly, the device-to-device reproducibility of the half-cell potential ionic liquid-based reference electrode, in particular of solid contact devices, has only drawn more attention quite recently, probably partly because this value is often more likely affected by other materials than by the ionic liquid itself. For electrodes with an ionic liquid-doped poly(vinyl chloride) reference membrane and a CIM carbon/redox buffer as the solid contact this value was reduced to ± 2.8 mV [63].

Another important characteristic of reference electrodes is their electrical resistance. The relatively few studies on ionic liquid based reference electrodes that reported on this characteristic reported values between roughly 100 kΩ to several MΩ values that will evidently vary also with the dimensions of the ionic liquid containing phase [67, 68, 71, 72, 78]. These resistances are higher than for aqueous salt bridges of comparable dimensions, which can be readily explained by the higher mobilities of the ions of a conventional salt bridge ions in water as compared to the mobilities of ionic liquid ions in neat ionic liquids or blends with a polymer, but they are compatible with most modern potentiometers. However, electrical resistances are of interest in the exploration of new ionic liquid blends with polymers. Among a number of different reference electrodes fabricated using blends of ionic liquids and various silicones, only the one with the lowest electrical resistance exhibited sample-independent potentials. Differential scanning calorimetry showed phase separation for several ionic liquid/polymer blends with high electrical resistance, lowering the concentration of the ionic liquid in the polymer phase [72]. However, it can be difficult to predict which ionic liquids phase separate and which ones will dissolve freely in a given polymer matrix. The dependence of the half-cell potentials for reference electrodes with such membranes is likely also related to the presence of ionic impurities in the silicone.

Lindner and co-workers assert that the limited reproducibility of the performance of ionic liquid based reference electrodes is one of the factors that inhibits currently the more widespread use of ionic liquid reference electrodes [66]. They argue that this low reproducibility may be largely due to impurities in the ionic liquids and in the polymer matrixes. Of particular concern are ionic liquids that do not contain the ionic liquid anion and cation in a perfect 1:1 ratio, but instead contain one of the two in excess, paired often with a hydrophilic counter ion. This was illustrated nicely by the deliberate preparation of the ionic liquid tetradodecylammonium tetrakis(pentafluorophenyl)borate with an impurity of tetradodecylammonium chloride, resulting in small excess of the lipophilic cations as compared to lipophilic anions. Without further action, ionic liquid based reference electrodes exhibited a response to salicylate with a slope of − 39 mV/decade. However, addition of sodium tetrakis(pentafluorophenyl)borate to the "contaminated" ionic liquid in an amount roughly equal to the tetradodecylammonium chloride reduce the slope for the salicylate response to 4.1 mV/decade, presumably because this resulted in the loss of NaCl into the aqueous solution and, thereby, in situ formation of the ionic liquid tetradodecylammonium tetrakis(pentafluorophenyl)borate ionic liquid in an amount roughly equal to the original "impurity". Notably, when ionic liquid reference electrodes are used in flowing samples, their half-cell potential has been observed to depend on the flow rate of the sample, which may be related to the kinetics of leaching of impurities from the reference electrode membrane into the sample [66]. More work will need to be performed to understand this effect more thoroughly and permit a reliable and predictable behavior of ionic liquid based reference electrodes.

Conclusions

There is no reference electrode that works well under all circumstances, and many characteristics must be considered when choosing the best reference electrode for any particular application. While many reference electrodes rely on a Ag/AgCl inner reference electrode along with a conventional liquid salt bridge, such electrodes are not practical for long-term experiments in small samples due to the contamination of sample solutions with bridge electrolyte, in particular if the junction is free-flowing and, therefore, electrolyte often needs to be refilled. Restrictions of the flow through nanoporous glass or other frit materials allow for longer term use, but this leads to charge screening in low ionic strength samples and contamination of the salt bridge. Micrometer sized capillaries with free-flowing electrolyte alleviate such limitations, keeping potential drifts as low as a few microvolts over several weeks. Further improvements are likely to be gained from more attention to the stability and reproducibility of the AgCl/Ag reference.

Solid-contact reference electrodes are diverse in their makeup and in their reported characteristics, each with their own limitations and benefits, making it difficult to systematically compare them to one another. When choosing a solid contact reference electrode, attention must be given to the needs of the particular application, such as long-term stability, device-to-device reproducibility for calibration-free applications, and longer shelf-lives for infrequent use. As solid-contact ISEs too, solid-contact reference electrodes will undoubtedly benefit in the coming years from the ongoing high research activity in the field of solid-contact electrodes.

Ionic liquid reference electrodes are proving to be a viable option in many electrochemical experiments, as a number of deficiencies of conventional salt bridges can be avoided, such as the need to replenish the bridge electrolyte and the need for a physical constraint to separate the inner filling solution and sample. Compatibility of the ionic liquid with the sample and the unavoidable leaching of ionic liquid into samples will need further attention. There is also still a need for guidance of users in selecting ionic liquids that are most suitable for particular applications.

References

1. T.J. Smith, K.J. Stevenson, Reference electrodes, in *Handbook of electrochemistry*. ed. by C.G. Zoski (Springer, Heidelberg, 2007)
2. H. Kahlert, Reference electrodes, in *Electroanalytical methods*. ed. by F. Scholz (Springer, Heidelberg, 2005)
3. C.R. Rousseau, P. Bühlmann, TrAC. Trends Anal. Chem. **140**, 116277 (2021)
4. P. Lingenfelter, B. Bartoszewicz, J. Migdalski, T. Sokalski, M.M. Bucko, R. Filipek, A. Lewenstam, Membranes (Basel) **9**, 161 (2019)
5. G. Inzelt, A. Lewenstam, F. Scholz, *Handbook of reference electrodes* (Springer, Heidelberg, 2013)
6. H. Kahlert, Potentiometry, in *Electroanalytical methods*. ed. by F. Scholz (Springer, New York, 2005)
7. F. Scholz, Salt bridges and diaphragms, in *Handbook of reference electrodes*. ed. by G. Inzelt, A. Lewenstam, F. Scholz (Springer, Heidelberg, 2013)
8. J.H. Shim, J. Kim, G.S. Cha, H. Nam, R.J. White, H.S. White, R.B. Brown, Anal. Chem. **79**, 3568 (2007)
9. D.T. Sawyer, A. Sobkowiak, J.L. Roberts Jr., *Electrochemistry for chemists* (Wiley, New York, 1995)
10. H. Suzuki, A. Hiratsuka, S. Sasaki, I. Karube, Sens. Actuators B **46**, 104 (1997)
11. H. Suzuki, T. Hirakawa, S. Sasaki, I. Karube, Sens. Actuators B **46**, 146 (1998)

12. J. Hu, A. Stein, P. Bühlmann, TrAC Trends Anal. Chem. **76**, 102 (2016)
13. B. Rostami, S.I. Mirzaei, A. Zamani, A. Simchi, M. Fardmanesh, Eng. Res. Express **1**, 015039 (2019)
14. P.J. Brewer, R.J. Leese, R.J.C. Brown, Electrochim. Acta **71**, 252 (2012)
15. R.E. Dohner, D. Wegmann, W.E. Morf, W. Simon, Anal. Chem. **58**, 2585 (1986)
16. H. Uematsu, T. Kono, S. Usui, T. Aomi, Denki Kagaku **55**, 532 (1987)
17. C.Z. Lai, M.A. Fierke, A. Stein, P. Bühlmann, Anal. Chem. **79**, 4621 (2007)
18. M.P.S. Mousavi, S.A. Saba, E.L. Anderson, M.A. Hillmyer, P. Bühlmann, Anal. Chem. **88**, 8706 (2016)
19. R.W. Bosch, S. Straetmans, S. Van Dyck, J. Mater. Sci. **37**, 3973 (2002)
20. W.N. Carson, C.E. Michelson, K. Koyama, Anal. Chem. **27**, 472 (1955)
21. M.P.S. Mousavi, P. Bühlmann, Anal. Chem. **85**, 8895 (2013)
22. E.L. Anderson, B.K. Troudt, P. Bühlmann, Anal. Sci. **36**, 187 (2020)
23. E.L. Anderson, S.A. Saba, D.J. Loomis, P. Bühlmann, M.A. Hillmyer, A.C.S. Appl, Nano Mater. **1**, 139 (2017)
24. E.L. Anderson, T.P. Lodge, T. Gopinath, G. Veglia, P. Bühlmann, Anal. Chem. **91**, 7698 (2019)
25. S. Higuchi, S. Takamatsu, T. Itoh, IEEE Sensors, 1411 (2019)
26. S. Higuchi, S. Takamatsu, T. Itoh, H. Okada, IEEE Sensors, 1 (2021)
27. S. Higuchi, H. Okada, S. Takamatsu, T. Itoh, Sensors (Basel) **20**, 1249 (2020)
28. E.L. Anderson, B.K. Troudt, P. Bühlmann, ACS Sens. **6**, 2211 (2021)
29. S.T. Broadley, T.Y. Chen, F.G. Gao, P.M. Payne, H.P. Silverman, ECS Trans. **1**, 1 (2006)
30. H. Nose, E. Sugimoto, T. Morimoto, S. Usui, T. Aomi, Jpn. J. Physiol. **36**, 607 (1986)
31. T. Kitade, K. Kitamura, S. Takegami, Y. Miyata, M. Nagatomo, T. Sakaguchi, M. Furukawa, Anal. Sci. **21**, 907 (2005)
32. K. Maksymiuk, A. Michalska, A. Kisiel, Z. Galus, Silver electrodes, in *Handbook of reference electrodes*. ed. by G. Inzelt, A. Lewenstam, F. Scholz (Springer, Heidelberg, 2013)
33. N.L. Walker, J.E. Dick, Anal. Chem. **93**, 10065 (2021)
34. D.S. Macedo, M. Vepsalainen, D. Acharya, C.D. Wood, D.C. Wen, L. Thomson, S. Peacock, T. Rodopoulos, C.F. Hogan, Electrochim. Acta **368**, 137636 (2021)
35. Z. Mousavi, K. Granholm, T. Sokalski, A. Lewenstam, Analyst **138**, 5216 (2013)
36. A. Lewenstam, T. Blaz, J. Migdalski, Anal. Chem. **89**, 1068 (2017)
37. U. Mattinen, J. Bobacka, A. Lewenstam, Electroanalysis **2009**, 21 (1955)
38. P. Sjoberg, A. Maattanen, U. Vanamo, M. Novell, P. Ihalainen, F.J. Andrade, J. Bobacka, J. Peltonen, Sens. Actuators B **224**, 325 (2016)
39. A. Kisiel, H. Marcisz, A. Michalska, K. Maksymiuk, Analyst **130**, 1655 (2005)
40. H. Xu, Y.W. Pan, Y. Wang, G. Li, Y. Chen, Y. Ye, Meas Sci Technol **23**, 125101 (2012)
41. J. N. Xu, F. H. Li, C. Tian, Z. Q. Song, Q. B. An, J. Y. Wang, D. X. Han, L. Niu, Electrochim. Acta, 322 (2019)
42. W. Vonau, W. Oelssner, U. Guth, J. Henze, Sens. Actuators B **144**, 368 (2010)
43. A. Lewenstam, B. Bartoszewicz, J. Migdalski, A. Kochan, Electrochem. Commun. **109**, 106613 (2019)
44. K. Granholm, Z. Mousavi, T. Sokalski, A. Lewenstam, J. Solid State Electrochem. **18**, 607 (2014)
45. A. Kisiel, A. Michalska, K. Maksymiuk, E.A.H. Hall, Electroanalysis **20**, 318 (2008)
46. C.M. Jiang, Y. Yao, Y.L. Cai, J.F. Ping, Sens. Actuators B **283**, 284 (2019)
47. F.X. Rius-Ruiz, A. Kisiel, A. Michalska, K. Maksymiuk, J. Riu, F.X. Rius, Anal. Bioanal. Chem. **399**, 3613 (2011)
48. A. Kisiel, M. Donten, J. Mieczkowski, F.X. Rius-Ruiz, K. Maksymiuk, A. Michalska, Analyst **135**, 2420 (2010)
49. A. Kisiel, K. Kijewska, M. Mazur, K. Maksymiuk, A. Michalska, Electroanalysis **24**, 165 (2012)
50. A. Bananezhad, M. Jovic, L.F. Villalobos, K.V. Agrawal, M.R. Ganjali, H.H. Girault, J. Electroanal. Chem. **847**, 113241 (2019)
51. W. Lonsdale, M. Wajrak, K. Alameh, Sensors **17**, 42 (2017)
52. T. Guinovart, G.A. Crespo, F.X. Rius, F.J. Andrade, Anal. Chim. Acta **821**, 72 (2014)
53. Z. Mousavi, K. Granholm, T. Sokalski, A. Lewenstam, Sens. Actuators B **207**, 895 (2015)
54. Ł Tymecki, E. Zwierkowska, R. Koncki, Anal. Chim. Acta **526**, 3 (2004)
55. T. Kakiuchi, N. Tsujioka, S. Kurita, Y. Iwami, Electrochem. Commun. **5**, 159 (2003)
56. T. Kakiuchi, Electrochem. Commun. **45**, 37 (2014)
57. Y. Fujino, T. Kakiuchi, J. Electroanal. Chem. **651**, 61 (2011)
58. H. Sakaida, Y. Kitazumi, T. Kakiuchi, Talanta **83**, 663 (2010)
59. L. Zhang, T. Miyazawa, Y. Kitazumi, T. Kakiuchi, Anal. Chem. **84**, 3461 (2012)
60. T. Kakiuchi, T. Yoshimatsu, Bull. Chem. Soc. Jpn. **79**, 1017 (2006)
61. M.P.S. Mousavi, M.K. Abd El-Rahman, E.K.W. Tan, H.H. Sigurslid, N. Arkan, J.S. Lane, G.M. Whitesides, P. Bühlmann, Sens. Actuators B **301**, 127112 (2019)
62. T. Zhang, C.Z. Lai, M.A. Fierke, A. Stein, P. Bühlmann, Anal. Chem. **84**, 7771 (2012)
63. J. Hu, K.T. Ho, X.U. Zou, W.H. Smyrl, A. Stein, P. Bühlmann, Anal. Chem. **87**, 2981 (2015)
64. J. Hu, A. Stein, P. Bühlmann, Angew. Chem. **55**, 7544 (2016)
65. D. Cicmil, S. Anastasova, A. Kavanagh, D. Diamond, U. Mattinen, J. Bobacka, A. Lewenstam, A. Radu, Electroanalysis **2011**, 23 (1881)
66. E. Lindner, M. Guzinski, T.A. Khan, B.D. Pendley, ACS Sens. **4**, 549 (2019)
67. E.L. Anderson, S.A. Chopade, B. Spindler, A. Stein, T.P. Lodge, M.A. Hillmyer, P. Bühlmann, Anal. Chem. **92**, 7621 (2020)
68. S.A. Chopade, E.L. Anderson, P.W. Schmidt, T.P. Lodge, M.A. Hillmyer, P. Bühlmann, ACS Sens. **2**, 1498 (2017)
69. C. Zuliani, G. Matzeu, D. Diamond, Talanta **125**, 58 (2014)
70. T. Kakiuchi, T. Yoshimatsu, N. Nishi, Anal. Chem. **79**, 7187 (2007)
71. M. Shibata, M. Yamanuki, Y. Iwamoto, S. Nomura, T. Kakiuchi, Anal. Sci. **26**, 1203 (2010)
72. X.V. Chen, A. Stein, P. Bühlmann, ACS Sens. **5**, 1717 (2020)
73. E. Lindner, V.V. Cosofret, S. Ufer, R.P. Buck, W.J. Kao, M.R. Neuman, J.M. Anderson, J. Biomed Mater. Res. **28**, 591 (1994)
74. Y. Kudo, M. Shibata, S. Nomura, N. Ogawa, Anal. Sci. **33**, 739 (2017)
75. T. Yoshimatsu, T. Kakiuchi, Anal. Sci. **23**, 1049 (2007)
76. M. Shibata, M. Yamanuki, Y. Iwamoto, S. Nomura, T. Kakiuchi, Anal. Sci. **26**, 1203 (2012)

77. T. Kakiuchi, J. Solid State Electrochem. **15**, 1661 (2011)
78. T.M. Galiullin, N.V. Pokhvishcheva, A.V. Kalinichev, M.A. Peshkova, Electroanalysis **31**, 1708 (2019)

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