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Short communication

Electrically driven elution in digital protein a membrane chromatography: An alternative to traditional low-pH elution

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ABSTRACT

Digital Protein A Membrane Chromatography (DMC^{PrA}) introduces an innovative antibody purification method that enables gentle elution using electrical fields rather than conventional low-pH buffers. By eliminating acidic conditions, DMC^{PrA} mitigates antibody degradation and aggregation associated with traditional Protein A chromatography. In this study, we investigated electrically driven elution in preparative Protein A membrane chromatography with the i3 DMC^{PrA} device (i3 Membrane GmbH, Radeberg, Germany). The effects of applied voltage, buffer composition, and salt type and concentration were systematically evaluated to clarify the underlying elution mechanisms. Effective elution occurred only with low-conductivity buffers and solutions, requiring specific salts at appropriate concentrations, for example 0.15 mM Na_2SO_4 or 1.0 mM NaCl, which yielded high antibody recovery. Applying voltage to induce elution, showed consistent pH shifts. When the electric field was oriented from anode to cathode, the pH increased, representing the optimal condition for voltage-driven elution; reversing polarity decreased the pH. The results support the hypothesis that the elution mechanism is primarily driven by electrochemical reactions at the electrodes, leading to water electrolysis. Hydroxide ions resulting from cathodic hydrogen evolution reactions (HER) increase pH, while protons from anodic oxygen evolution reactions (OER) likely induce conformational changes in Protein A and IgG, initiating elution. These reactions are strongly influenced by the applied voltage as well as the chemical composition and ionic properties of the buffers. Collectively, these parameters exert a significant impact on elution efficiency and reproducibility. This work demonstrates that electrically driven elution provides a promising alternative to low-pH based methods, enabling milder purification of antibodies through electrochemical modulation.

1. Introduction

Affinity chromatography is a fundamental step in downstream antibody purification, with Protein A (PrA) being the most widely used affinity ligand system for this purpose. This preference arises from its high selectivity and binding affinity toward the Fc region of IgG [1], enabling purities greater than 90 % [2]. The inherent limitations of resin-based PrA chromatography, including low productivity and prolonged processing times, have been effectively addressed through the development of membrane-based chromatography systems. These membranes enable substantially higher binding capacities at elevated flow rates by facilitating convective mass transport rather than relying on diffusion, thereby mitigating the mass transfer limitations characteristic of particle-based media [3–5]. Nevertheless, a persistent drawback of conventional PrA chromatography lies in its standard elution protocol, which typically employs acidic buffers within the pH range of 3 to 4 [1]. Such low-pH elution conditions can promote antibody aggregation and thus comprising the potency and safety of the therapeutic product [6,7]

Digital Protein A Membrane Chromatography (DMC^{PrA}) represents an innovative antibody purification method that combines the advantages of PrA membrane chromatography while eliminating the need for conventional low-pH elution buffers. This approach mitigates antibody degradation and aggregation typically associated with traditional PrA chromatography by enabling elution through the application of electrical fields instead of acidic buffers. DMC streamlines the workflow and reduces processing time by removing the need for buffer exchange throughout and after purification [8]

The mechanistic understanding of voltage-induced elution in chromatography, particularly in Protein A membrane chromatography, remains limited, with only a few studies addressing this concept to date [8, 9]. Moreover, the impact of key process parameters on voltage-induced

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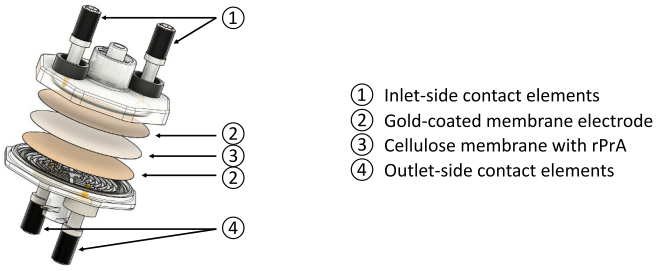

Fig. 1. Design of i3 DMC^{PrA} device in an exploded view.

elution has not yet been systematically investigated and therefore remains unclear. In this manuscript, we provide a mechanistic explanation of voltage-induced elution and systematically evaluate the influence of critical process parameters. The findings are further supported by a scale-up study, demonstrating the method's potential for preparative applications.

2. Material and methods

Digital Membrane Chromatography (DMC) was carried out on an ÄKTA Purifier system (Cytiva) using the commercially available i3 DMC^{PrA} Protein A device (i3 Membrane, Radeberg, Germany). The device is composed of two gold-sputtered PET membranes, with the Protein A membrane sandwiched between them (see Fig. 1). The Protein A membrane volume (MV) is 0.04 mL. Voltage is applied via four electrical contact elements integrated into the device housing and controlled externally using the i3 DMC$_{control}$ unit. Scale-up experiments were performed using a 1.0 mL prototype device with the same sandwich configuration, employing the same electrodes and Protein A membrane provided by i3 Membrane. Phosphate buffered saline (PBS) with 1:50 dilution (200 μM Na_2HPO_4, 36 μM KH_2PO_4, 2.7 mM NaCl, 54 μM KCl) served as standard buffer throughout the runs. Any modifications to the mobile phase are mentioned directly in the results section for the corresponding experiment. After connecting the device to the ÄKTA system, the mobile phase is pumped isocratically at a flow rate of 2 mL/min. The run includes an equilibration step (5 mL), a wash step (5–10 mL), a DMC elution, and a post-DMC wash step (10 mL). For electrically driven elution, voltage was applied externally using the i3 DMC$_{control}$ unit (i3 Membrane, Radeberg, Germany) connected to the membrane module. Standard DMC elution conditions were +2 V applied for 2 min or 3 min. An additional control elution (also referred to as strip in this study) with 0.1 M citrate buffer (pH 3.0) was performed after each run to benchmark DMC-based elution against conventional low-pH elution. A commercially available Trastuzumab-based monoclonal antibody (Trazimera®, Pfizer, Berlin, Germany; pI ≈ 8.7) was used as the model antibody in all experiments. The sample was either dissolved in ultrapure water or 1:50 PBS to a final concentration of 1.2 mg/mL and a standard load of 30 mg/mL·MV was applied for the small device, whereas 24 mg/mL·MV was used for the 1.0 mL device. In addition, in-line monitoring was performed for UV absorbance at 280 nm, pH, and conductivity during all experiments.

3. Results and discussion

In a standard run using low-conductivity phosphate-buffered saline (PBS, 1:50 dilution) and a voltage of +2 V for 2 min for elution, a pronounced change in pH was observed concurrent with the elution peak (Fig. 2A). After the pH reached its maximum, it gradually declined during continued voltage application, remaining slightly above the pH of the equilibration solution. Upon voltage termination, the pH dropped rapidly and then slowly returned toward the buffer pH. The control elution/ strip at pH 3 showed a mAb peak of about < 5 % only. Additional experiments (not shown) confirmed that elution occurs only with low-conductivity buffers and a voltage-induced pH shift. Voltage-driven elution could not be achieved with undiluted PBS, and although 1:5 and 1:10 PBS dilutions supported DMC elution, the 1:50 dilution provided the highest recovery of > 95 % and the smallest eluate volume. To reach the low conductivity of the standard running buffer, 22 MV of post-loading wash are required for the small device and 4 MV for the 1.0 mL device. The higher requirement of 22 MV arises from its large hold-up volume compared to the membrane volume within the smaller device. In contrast, the scaled-up device has a smaller ratio between hold-up volume and membrane volume, reducing the required wash volume to 4 MV to reach the needed lower conductivity. This volume falls well within typical the typical range used for a post-loading wash in membrane chromatography. To further investigate the mechanism underlying voltage-induced antibody elution, and to determine whether pH changes drive antibody release, several experimental parameters were systematically varied during DMC elution. One key parameter was the applied voltage, which was tested in a range from 1.5 V to 2.5 V, with a constant application of 2 min. As shown in Fig. 2B, the pH increase was dependent on the applied voltage: higher voltages led to slightly higher pH maximum and a more pronounced drop post voltage application. In addition to the pH drop observed after voltage termination, voltage-dependent pH changes were also detected during the voltage-application period. While the pH remained at the maximum pH at 1.5 V and 1.6 V, it began to decrease at voltages above 1.7 V, with the onset of the decline occurring earlier at higher voltages. No voltage-driven elution was observed at 1.5 V; despite the pH increase, the entire antibody eluted only during the subsequent low-pH strip. Minor voltage-induced elution was first detected at 1.6 V and increased progressively with higher voltages. Optimal antibody recovery (> 95 %) with minimal eluate volume was achieved at 2.0 V and 2.5 V, with only negligible elution during the low-pH strip. These observations clearly demonstrate that the elution is not driven by the initial increase in pH, but rather by the subsequent decrease during the voltage-on phase.

To assess whether the observed pH shifts were specific to interactions involving the Protein A (PrA) ligand or the monoclonal antibody (mAb), further control experiments were performed. These included runs without antibody loading (Fig. 3A/B), as well as using different membrane types: anion-exchange, cation-exchange, and ligand-free membranes (Fig. 3B). All conditions produced comparable pH responses to applied voltage, indicating that the pH shift is not ligand- or antibody-specific, but rather a general electrochemical effect within the system.

Moreover, polarity reversal experiments provided further insight into the mechanism. When a positive voltage was applied, establishing an electric field oriented from anode to cathode (as defined by the manufacturer), a pH increase was consistently observed during voltage application. In contrast, when a negative voltage was applied – thus reversing the field orientation from cathode to anode in flow direction – an inverse pH trend was observed, with pH decreasing upon voltage application and increasing after voltage termination. This trend was consistent across ligand types (e.g., PrA in Fig. 3A) and also appeared in ligand-free membranes (Fig. 3B).

The practical cell voltage for water electrolysis at gold electrodes is estimated to exceed 2.3 V, based on reported half-cell overpotentials for the oxygen evolution reaction (OER, onset at ~2.0 V vs. RHE) [10] and hydrogen evolution reaction (HER) [11] at polycrystalline gold electrodes. Nevertheless, water splitting remains thermodynamically feasible at all applied cell voltages (1.5–2.5 V), as they exceed the thermodynamic minimum of 1.23 V. We therefore propose that the pH shifts are driven by electrochemical processes associated with water electrolysis, involving OER occurring at the anode and HER at the

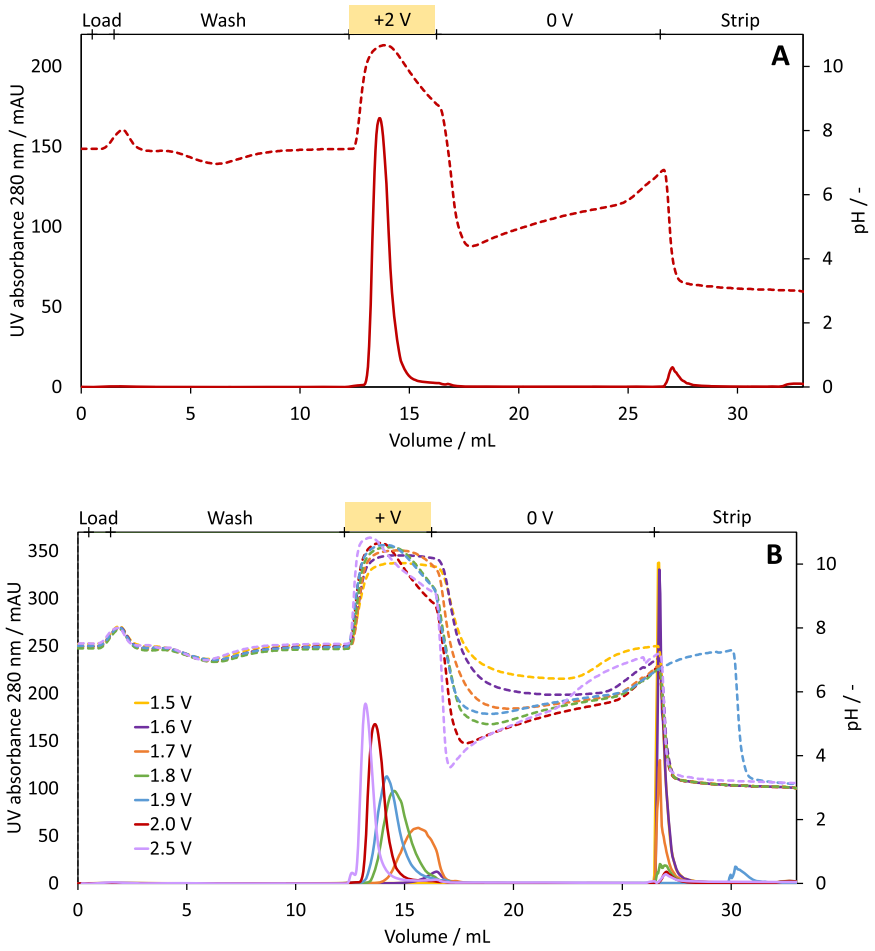

Fig. 2. Chromatograms of Trastuzumab capture using the i3 DMC^{PrA} device with DMC elution are shown. (A) Elution at 2 V and (B) elution with variable voltage (1.5–2.5 V for 2 min) were performed using PBS (1:50) as the mobile phase at a flow rate of 2 mL/min. A total of 1 mL of Trazimera® (1.2 mg/mL in ultrapure water) was loaded onto the membrane. Following DMC elution, control elution/strip steps were carried out using 0.1 M citrate buffer (pH 3.0). Solid lines represent UV absorbance at 280 nm, and dashed lines represent pH profiles.

cathode. Under near-neutral pH conditions and in the absence of buffering species, these reactions take place as described by T. Naito et al. [12], as follows:

Anode: $2\,H_2O \rightleftharpoons O_2 + 4\,H^+ + 4\,e^-$ (1)

(OER) $4\,OH^- \rightleftharpoons O_2 + 2\,H_2O + 4\,e^-$ (2)

Cathode: $2\,H_2O + 2\,e^- \rightleftharpoons H_2 + 2\,OH^-$ (3)

(HER) $2\,H^+ + 2\,e^- \rightleftharpoons H_2$ (4)

With changing pH, different reactions may dominate, but we assume that reactions (1) and (3) occur predominantly under near neutral pH and account for the observed pH trends [13]. With the electric field oriented from anode to cathode in the direction of flow, as in standard DMC elution with positive voltages, the observed pH increase can be attributed to hydroxide ions (OH^-) generated by the cathodic HER [Eq. (3)]. In this configuration, the cathode is located at the device outlet, allowing the hydroxide ions formed to exit the system directly and raise the effluent pH. The subsequent decrease and levelling off of the pH during the voltage-on period is most likely caused by neutralization of OH^- by hydronium ions (H_3O^+) generated at the anode via the OER [Eq. (1)]. Once the voltage has been switched off, the residual H_3O^+ ions within the module are flushed towards the outlet by the buffer flow. Without concurrent OH^- production to offset the acidity, this gives rise to the observed transient pH drop. The buffer flow then restores the system to its baseline pH. Upon polarity reversal, while maintaining the same flow direction, the anode becomes the device outlet, inverting the observed pH trend. The immediate pH decrease during voltage application can be attributed to H_3O^+ generated by the anodic OER [Eq. (1)], which exit the system directly at the outlet. The subsequent partial pH recovery during the voltage-on period is most likely caused by OH^- produced via the cathodic HER [Eq. (3)], which migrate toward the outlet and partially offset the H_3O^+-induced pH decease. Once the voltage is switched off, the residual OH^- ions within the module are flushed toward the outlet by the buffer flow. Without concurrent H_3O^+ production at the anode to offset the basicity, this gives rise to a transient pH increase before the buffer flow restores the system to its baseline pH. Applying a voltage of −2 V combined with flow reversal restored the original pH response observed at +2 V (data not shown).

The elution mechanism underlying voltage-induced elution in a PrA membrane is hypothesized to involve H_3O^+ ions generated by the anodic oxygen evolution reaction (OER). These ions are transported through the Protein A membrane, leading to a local pH decrease in the membrane before passing through the perforated cathode. H_3O^+ ions have been shown to induce conformational changes in both PrA and IgG, thereby facilitating elution in a manner analogous to conventional low-pH elution [14]. However, this local effect is not reflected in the pH measured by the ÄKTA system. We therefore distinguish between the measured bulk pH at the outlet, which is elevated due to OH^- produced by the cathodic HER, and the local pH in the anode-side Protein A

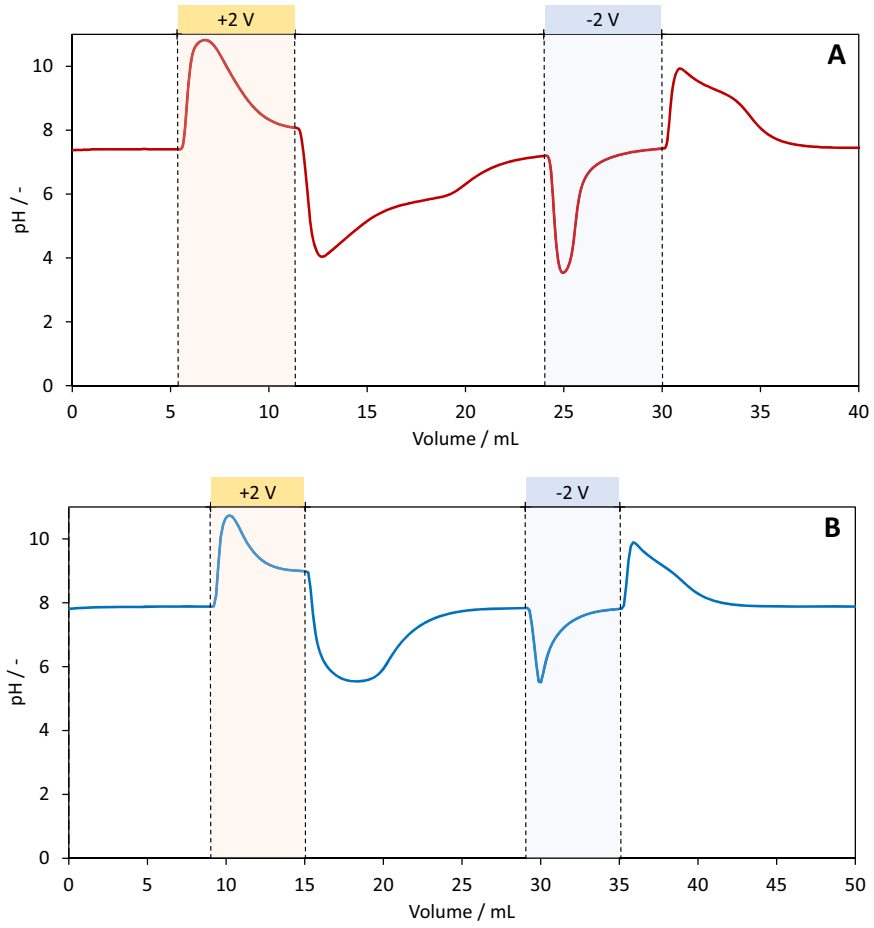

Fig. 3. pH profiles recorded during and after application of ±2 V for 2 min or 3 min without sample load using the i3 DMC device with (A) Protein A membrane and (B) membrane without ligand. The runs were performed using PBS (1:50) as the mobile phase at a flow rate of 2 mL/min. All conditions produced comp arable pH responses to applied voltage.

membrane, which proposed to govern the elution mechanism. As the mobile phase flows through the cathode, the anodically generated H_3O^+ ions are partially neutralized by the OH^- produced via HER [Eq. (3)], with excess OH^- continuously flushed toward the outlet, accounting for the observed alkaline bulk pH. Assuming that only the reactions described in Eq. (1) and Eq. (3) occur at equal rate, no change in the outlet pH is expected following a prolonged voltage application. However, the elution mechanism is more complex, as different ions may influence the relative rates of these reactions. As shown by Monteiro et al. [15], both the identity and concentration of alkali metal cations influence the kinetics of the HER on gold electrodes: weakly hydrated cations (e.g., K^+) promote the HER, whereas strongly hydrated cations (e.g., Li^+) inhibit it.

In addition to electrochemical reactions at the electrodes, an applied electric potential induces the formation of the electrochemical double layers on the electrode surfaces. Ghisellini et al. demonstrated that conformational changes in Protein A/mAb complexes immobilized directly on a gold electrode surface occur upon application of an electric potential, although dissociation of the complex was not observed [16]. In the present system, no proteins are immobilized on the electrode surfaces, and the Protein A membrane is positioned 20 μm from the electrodes, well beyond the effective range of the electrochemical double layer (Deybe length ≈ 10 nm at 1 mM NaCl). The electrode double layer effect on the Protein A/antibody interaction can therefore be disregarded.

The applied electric field does, however, interact with the Protein A/antibody complex within the membrane, as both immobilized Protein A and the complexed antibodies carry net charges at physiological pH. Morgan et al. demonstrated that antibodies can be eluted electrophoretically from a Protein A gel [17]. This process is, however, considerably slow and is likely not attributed to a direct weakening of the Protein A/antibody interaction. Rather, it has been proposed that spontaneous dissociation of the complex leads to the release of the antibody, which is subsequently separated electrophoretically from the immobilized Protein A, thereby preventing reassociation [18]. Since elution can occur within 1 min under our conditions and we applied a convective flow of the mobile phase, electrophoretic effects can initially be discharged.

To evaluate whether specific salts influence elution behaviour in digital membrane chromatography (DMC), additional experiments were conducted using various salts and concentrations. Starting from the standard 1:50 PBS solution (200 μM Na_2HPO_4, 36 μM KH_2PO_4, 2.7 mM NaCl, 54 μM KCl), KCl and NaCl were individually omitted to assess the effect of the remaining phosphate components (Na_2HPO_4 and KH_2PO_4). The resulting solution, lacking KCl and NaCl, is referred to as PB (1:50). As shown in Fig. 4A, in the absence of NaCl, no elution was observed under these conditions, despite a measurable pH increase. The main difference that was observed apart from the missing elution using solely the phosphate salts, is the less pronounced decrease of pH after DMC-termination. Increasing the concentration of phosphate salts (results not shown), and thereby the conductivity, also did not result in sufficient elution compared to solutions containing NaCl. These observations indicate that the underlying elution mechanism is highly complex and strongly dependent on specific ions present. The process exhibits pronounced ions specificity, and drawing comprehensive conclusions about the sum of electrochemical and physiochemical reactions occurring within the device when different salts are used remains challenging.

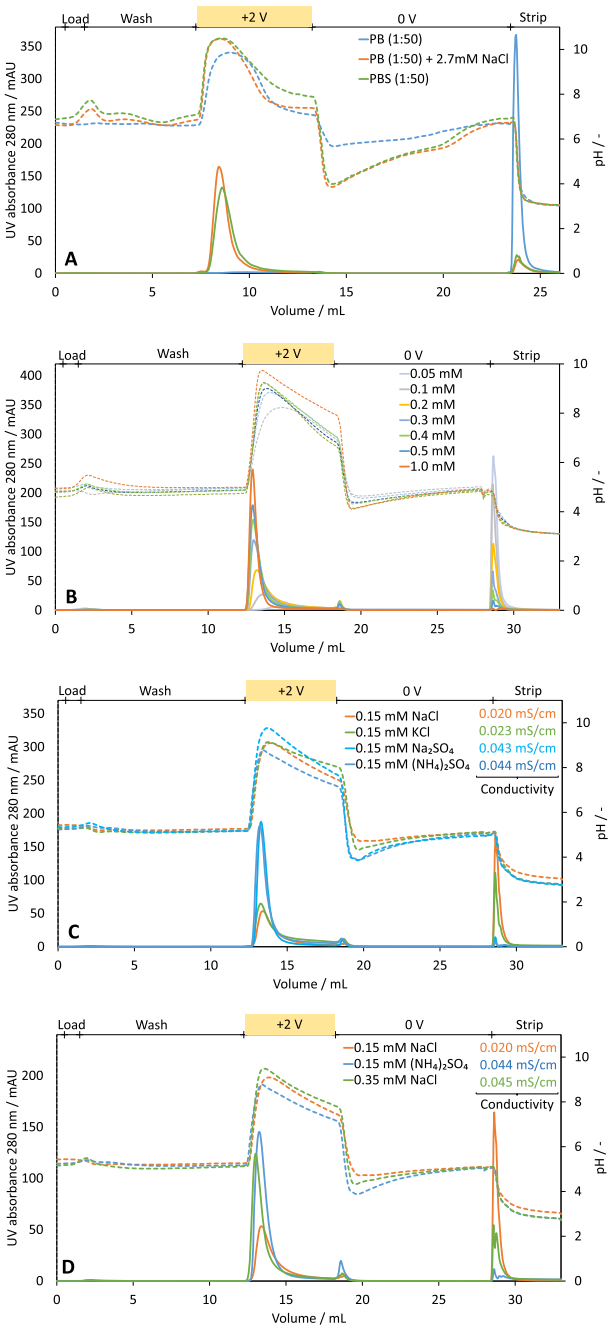

Fig. 4. Chromatograms of Trastuzumab capture using the i3 DMC^{PrA} device under varying salt types and concentrations during DMC elution are shown. (A) Phosphate buffered saline (PBS, 1:50) was compared to KCl- and NaCl-free phosphate buffer (PB, 1:50), and PB (1:50) supplemented with NaCl. (B) Different NaCl concentrations and (C) various salts dissolved in ultrapure water were further evaluated (D) with matching the conductivity of two different salts. DMC elution was performed at 2 V for 3 min. A total of 1 mL of Trazimera® (1.2 mg/mL in ultrapure water) was loaded onto the membrane. Following DMC elution, control elution/strip steps were carried out using 0.1 M citrate buffer (pH 3.0). Solid lines represent UV absorbance at 280 nm, and dashed lines represent pH profiles.

To investigate whether NaCl, or more specifically chloride ions, are required to facilitate elution, further experiments were performed using NaCl in ultrapure water at varying concentrations (Fig. 4B). The results indicate that even a low concentration of 0.05 mM NaCl enabled a small degree of elution at 2 V. Increasing the NaCl concentration up to 1.0 mM led to a proportional increase in antibody recovery, reaching complete elution at the highest concentration tested. Additional experiments were conducted using different salts at a fixed concentration of 0.15 mM to allow for comparative analysis under low-salt conditions (Fig. 4C). While NaCl and KCl exhibited similar behaviour in terms of pH change and elution efficiency, Na_2SO_4 and $(NH_4)_2SO_4$ resulted in higher antibody recoveries. Notably, $(NH_4)_2SO_4$ led to a smaller pH increase, likely due to the buffering effect of ammonium ions, which can react with hydroxide ions to form ammonia and water, thereby mitigating the rise in pH. In additional experiments, the influence of the conductivity was examined by increasing the NaCl concentration to 0.35 mM to match the conductivity of 0.15 mM $(NH_4)_2SO_4$ (Fig. 4D). Increasing the conductivity of the NaCl solution resulted in a voltage-induced elution peak comparable to that obtained with $(NH_4)_2SO_4$, demonstrating that conductivity is the critical parameter for voltage-induced elution in DMC. The lower yield with 0.15 mM NaCl is therefore attributed to its lower conductivity. Multivalent salts achieve the required conductivity at lower molar concentrations due to increased ion yield and the higher molar conductivity of multivalent anions such as SO_4^{2-}. These findings suggest that it is not chloride ions specifically that are required for elution. The observations further underline the strong dependence of water electrolysis reactions on the composition of the electrolyte. Lu et al. [19] reviewed that, in addition to alkali metal cations, anions such as halides and carbonates critically affect the kinetics of both the HER and OER.

In all of the experiments described above, with the electric field oriented in the preferred direction for effective elution (from anode to cathode), the collected elution pool was consistently alkaline (pH 9–10), even though we hypothesize that H_3O^+ ions are involved in the elution mechanism. SEC analysis revealed no evidence of aggregation or fragmentation, and a related study by Steegmüller et al. [9] likewise reported reduced aggregation of voltage-induced eluted antibodies compared with conventional low-pH elution. Since the manufacturer permits alkaline cleaning with 0.1 M NaOH, it is anticipated that the Protein A ligand will also remain stable at this pH level. Nevertheless, several neutralization strategies were evaluated to minimize exposure of the antibodies to alkaline conditions. The most straightforward approach involved collecting both the high-pH eluate during DMC and the lower-pH fractions obtained after DMC termination, leading to neutralization of the combined eluate pool. To further enhance the pH decrease, a negative voltage was applied to reverse the polarization of the electric field rather than simply switching off the DMC. Previous experiments demonstrated that reversing the polarity decreased the pH more effectively than terminating the voltage alone. Additional studies varying the voltage-on time during elution showed that 40 s was sufficient to achieve high yield. Accordingly, as shown in Fig. 5A, the small-scale device (0.04 mL membrane volume, MV) yielded 1.9 mL of eluate with a pH of 7.96 when 2.5 V was applied for 40 s, followed by −2.5 V for an additional 40 s, before returning to 0 V.

To demonstrate that voltage-driven elution is also applicable at larger scale, a device with a membrane volume (MV) of 1 mL was assembled. This setup exhibited a comparable pH profile during voltage application and after voltage termination. However, a higher voltage (3.25 V) was required to achieve sufficient elution efficiency (> 95 %) compared with the small-scale device. This increase was necessary because multiple PrA membrane layers were stacked on top of each other, resulting in a greater distance between the electrodes. To maintain the electric field required for efficient elution, a higher applied voltage was therefore needed. The same neutralization strategy used for the small-scale device was successfully implemented, with adjustments to the voltage magnitude and application time. As shown in Fig. 5B, this configuration yielded a total elution volume of 8.0 mL at pH 7.37 when 3.25 V was applied for 2 min, followed by −3.25 V for an additional 2 min, before returning to 0 V.

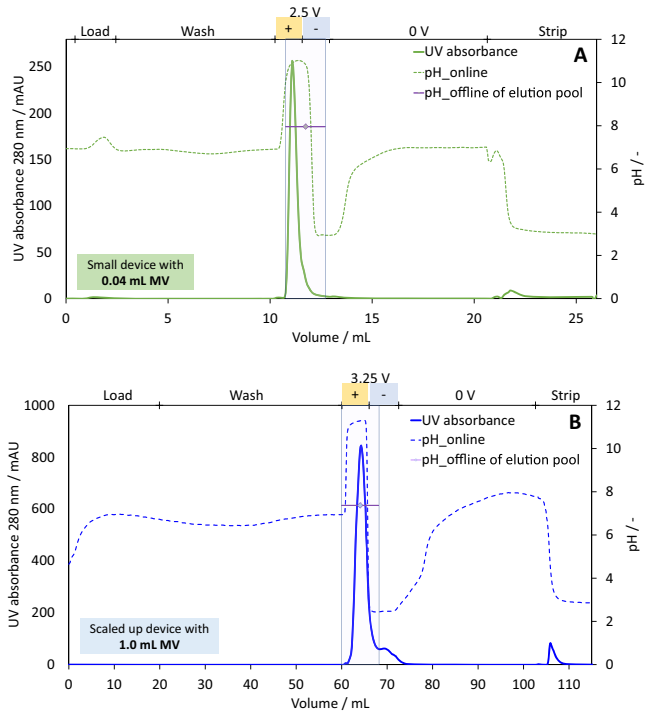

Fig. 5. Chromatograms of neutralization method of elution pool with A: small scale device (0.04 mL) and B: scaled up device (1 mL). Phosphate buffered saline (PBS, 1:50) was used as running solution and a total of 1 mL (A) and 20 mL (B) of Trazimera® (1.2 mg/mL in ultrapure water) was loaded onto the membrane. A: DMC elution was performed at +2.5 V for 40 s, followed by a switch to −2.5 V for 40 s. A total elution volume of 1.9 mL was collected, with a final pH of 7.96. B: DMC elution was performed at +3.25 V for 2 min, followed by a switch to −3.25 V for 2 min. This resulted in a total elution volume of 8.0 mL with a final pH of 7.37. Following DMC elution, control elution/strip steps were carried out using 0.1 M citrate buffer (pH 3.0). Solid lines represent UV absorbance at 280 nm, and dashed lines represent pH profiles.

4. Conclusion

The i3 DMC^{PrA} introduces a novel approach for rapid and efficient capture and release of monoclonal antibodies (mAbs) and other Fc-containing molecules. Its operation under low-salt conditions makes it particularly suitable for applications such as mass spectrometry, where minimal ionic strength is essential for accurate analysis. Elution is achieved using a single buffer and minimal salt, eliminating the need for buffer exchange and significantly reducing processing time compared to conventional workflows. The consistent pH shifts observed during elution are attributed to electrochemical reactions – oxygen evolution (OER) and hydrogen evolution (HER) – at the electrodes, which drive both the pH change and the elution process. Notably, these reactions are strongly influenced by the electrolyte composition. Furthermore, the voltage-induced elution demonstrated robust scalability, confirming its suitability for implementation in larger-scale devices while maintaining efficient performance.

CRediT authorship contribution statement

Sandeep Kaur: Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Jonas Kick:** Visualization, Methodology, Investigation, Formal analysis. **Christian Frech:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] A.M. Ramos-de-la-Peña, J. González-Valdez, O. Aguilar, Protein A chromatography: challenges and progress in the purification of monoclonal antibodies, J. Sep. Sci. 42 (2019) 1816–1827, https://doi.org/10.1002/jssc.201800963.
[2] H.F. Liu, J. Ma, C. Winter, R. Bayer, Recovery and purification process development for monoclonal antibody production, MAbs 2 (2010) 480–499, https://doi.org/10.4161/mabs.2.5.12645.
[3] J. Osuofa, S.M. Husson, Comparative evaluation of commercial protein A membranes for the rapid purification of antibodies, Membranes 13 (2023) 511, https://doi.org/10.3390/membranes13050511.
[4] J. Chen, B. Yu, H. Cong, Y. Shen, Recent development and application of membrane chromatography, Anal. Bioanal. Chem. 415 (2023) 45–65, https://doi.org/10.1007/s00216-022-04325-8.
[5] C. Boi, S. Dimartino, G.C. Sarti, Performance of a new protein A affinity membrane for the primary recovery of antibodies, Biotechnol. Prog. 24 (2008) 640–647, https://doi.org/10.1021/bp0704743.
[6] F.A.S. Wang, Y. Fan, W.K. Chung, A. Dutta, E. Fiedler, U. Haupts, J. Peyser, R. Kuriyel, Evaluation of mild pH elution protein A resins for antibodies and fc-fusion proteins, J. Chromatogr. A 1713 (2024) 464523, https://doi.org/10.1016/j.chroma.2023.464523.
[7] J. Scheffel, S. Hober, Highly selective Protein A resin allows for mild sodium chloride-mediated elution of antibodies, J. Chromatogr. A 1637 (2021) 461843, https://doi.org/10.1016/j.chroma.2020.461843.
[8] K. Müller, J. Rößler, A. Klassen, M. Pereira Silverio, F. Schmitt, H. Passuth, B. Siebels, H. Schlüter, M. Riedner, Digital membrane chromatography — a new way to rapid antibody purification for top-down mass spectrometry, ChemRxiv 2025 (n.d.). https://doi.org/10.26434/chemrxiv-2025-54k6j.
[9] T. Steegmüller, M. Nzokam, C. Sieg, D. Golonka, N. Fridley, S.P. Schwaminger, S. Berensmeier, Chromatography's evolution, unlocking affinity's new solution: potential-controlled affinity membrane chromatography, RSC Adv. 16 (n.d.) 6061–6068. https://doi.org/10.1039/d5ra08238b.
[10] G. Zwaschka, I. Nahalka, A. Marchioro, Y. Tong, S. Roke, R.K. Campen, Imaging the heterogeneity of the oxygen evolution reaction on gold electrodes operando: activity is highly local, ACS Catal 10 (2020) 6084–6093, https://doi.org/10.1021/acscatal.0c01177.
[11] M. Gandhi, Modelling prospects of bio-electrochemical immunosensing platforms, Electrochem 5 (2024) 146–161, https://doi.org/10.3390/electrochem5020010.
[12] T. Naito, T. Shinagawa, T. Nishimoto, K. Takanabe, Water electrolysis in saturated phosphate buffer at neutral pH, ChemSusChem 13 (2020) 5921–5933, https://doi.org/10.1002/cssc.202001886.
[13] A.R. Kucernak, H. Wang, X. Lin, Avoid using phosphate buffered saline (PBS) as an electrolyte for accurate OER studies, ACS Energy Lett 9 (2024) 3939–3946, https://doi.org/10.1021/acsenergylett.4c01589.
[14] M. Zarrineh, I.S. Mashhadi, M. Farhadpour, A. Ghassempour, Mechanism of antibodies purification by protein A, Anal. Biochem. 609 (2020) 113909, https://doi.org/10.1016/j.ab.2020.113909.
[15] M.C.O. Monteiro, A. Goyal, P. Moerland, M.T.M. Koper, Understanding cation trends for hydrogen evolution on platinum and gold electrodes in alkaline Media, ACS Catal 11 (2021) 14328–14335, https://doi.org/10.1021/acscatal.1c04268.
[16] P. Ghisellini, M. Caiazzo, A. Alessandrini, R. Eggenhöffner, M. Vassalli, P. Facci, Direct electrical control of IgG conformation and functional activity at surfaces, Sci. Rep. 6 (2016) 37779, https://doi.org/10.1038/srep37779.
[17] M.R.A. Morgan, E. George, P.D.G. Dean, Investigations into the controlling factors of electrophoretic desorption: a widely applicable, nonchaotropic elution technique in affinity chromatography, Anal. Biochem. 105 (1980) 1–5, https://doi.org/10.1016/0003-2697(80)90413-3.
[18] W.C. Olson, M.L. Yarmush, Electrophoretic elution from monoclonal antibody immunoadsorbents: a theoretical and experimental investigation of controlling parameters, Biotechnol. Prog. 3 (1987) 177–188, https://doi.org/10.1002/btpr.5420030309.
[19] X. Lu, W. Tu, Y. Zhou, Z. Zou, Effects of electrolyte ionic species on electrocatalytic reactions: advances, challenges, and perspectives, Adv. Energy Mater. 13 (2023) 2300628, https://doi.org/10.1002/aenm.202300628.