Supplementary Information (SI) for Lab on a Chip.
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**Table S1** Recent examples of μPADs (2018-2025) for medical diagnostic applications (immunoassays)
This is an extended version of Table 1 in the main text
Columns not shown in the main text tables are indicated with light blue colour column headings
(Blood separation) in parentheses indicates that no specific information is provided in the cited work. Since serrum is mentioned as the sample, a prior serum separation from whole blood is assumed

| Analyte | Sample matrix | Real sample test | Sample type subcategory | Sample volume (μL) | Detection technique | Detection range | Detection limit | Storage stability | Assay time | Number of flow channels | Off-device pretreatment | Operation steps | Reagent handling | External equipment | Sample volume | Article title | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tumor necrosis factor (TNF)α | Rat tissue sample | Clinical sample (rat) | S | 231.6 ± 103.09 (μL) (3 weeks after surgery)<br>69.9 ± 10.4 pM (2 days after surgery) | Colorimetric | N.A. | 22 μM<br>(PBS) | N.A. | 21 min | No | No | Sample application<br>Continuous flow of PBS | No<br>Microconcentrator dryers | Box with heater<br>Pump | 3 μL | A paper-based microfluidic platform with shape-memory-polymer-actuated fluid valves for automated multiplexed immunoassays | H. Hu, P. Song, Q. Wu, C. Zhao, P. Pan, X. Li, N. Y. K. Li-Jessen and X. Liu, Microsyst. Nanoeng., 2019, 5, 53 |
| Human interleukin-8 (IL-8) | Human saliva | Clinical sample | S | 3.2–22.5 pg/mL | Colored length | 0.03–25.0 pg/mL | 0.03 pg/mL | Sealed bag<br>4 °C<br>~7 weeks (no decrease)<br>~12 weeks (93.0%) | 35 min | Yes<br>Multiple operations | No | Sample application<br>Reagent application<br>Removal and insertion of paper bridge<br>Reagent application | Yes<br>HRP-antibody<br>$H_2O_2$ | No | 15 μL | Distance-Based All-in-One Immunodevice for Point-of-Care Monitoring of Cytokine Interleukin-8 | K. Khashorneatdul, W. Dungchai and N. Panree, ACS Sens., 2022, 7, 2410-2419 |
| Human interleukin-8 (IL-8) | Human urine | Clinical sample | S | 3.69–18.10 pg/mL | Colored length | 0.03–25.0 pg/mL | 0.03 pg/mL | Sealed bag<br>4 °C<br>~7 weeks (no decrease)<br>~12 weeks (93.0%) | 35 min | Yes<br>Multiple operations | No | Sample application<br>Reagent application<br>Removal and insertion of paper bridge<br>Reagent application | Yes<br>HRP-antibody<br>$H_2O_2$ | No | 15 μL | Distance-Based All-in-One Immunodevice for Point-of-Care Monitoring of Cytokine Interleukin-8 | K. Khashorneatdul, W. Dungchai and N. Panree, ACS Sens., 2022, 7, 2410-2419 |
| SARS-CoV-2 | Exhaled breath | Clinical sample | A | N.A. | Eschem (ZPV) | 3.7–10,000 ng/mL<br>(Exhaled Breath) | 3 ng/mL<br>(Exhaled Breath) | 4 °C<br>~7 days<br>~85% | 60 min | Yes<br>Multiple operations | Off-chip pond washing and detection | Reagent application<br>Off-site application<br>Off-chip washing and eschem measurement | Yes<br>Antibody<br>1-Naphthyl phosphate Disodium salt | Monolular<br>Potentiostat | >50 μL | Functionalized NIR Face Mask with a Chemical-Free Paper-Based Collector for Exhaled Breath Analysis: SARS-CoV-2 Detection with a Printed Immunosensor as a Case Study | L. Gutiérrez-Gálvez, N. Serdiuksz, L. Flors, L. Fabiani, T. García-Mendiola, B. Lorenzo and F. Antonio, ACS Sens., 2024, 9, 6347-6357 |
| Hepatitis B virus (HBV) | Human serum | Clinical sample | A | 44.61–420 pg/mL | Eschem (ZA) | 0.1–250 ng/mL<br>(PBS) | 8.2 pg/mL<br>(PBS) | -20 °C<br>>50 days<br>~90.5–108.6 % | <600 s | No<br>Immediate measurement | Blood separation | Sample application<br>Buffer application<br>Eschem measurement | No | Potentiostat | 15 μL | An automated fast-flow/delayed paper-based platform for the simultaneous electrochemical detection of hepatitis B virus and hepatitis C virus core antigen | S. Boonkaew, A. Yakoh, N. Chuaypen, P. Tangkijvanich, S. Rengpipat, W. Siangproh and O. Chailapakul, Biosens. Bioelectron., 2021, 193, 113543 |
| Hepatitis C virus (HCV) | Human serum | Clinical sample | A | 84.84–269.88 pg/mL | Eschem (ZA) | 0.001–250 ng/mL<br>(PBS) | 0.19 pg/mL<br>(PBS) | -20 °C<br>>50 days<br>~90.5–108.6 % | <600 s | No<br>Immediate measurement | Blood separation | Sample application<br>Buffer application<br>Eschem measurement | No | Potentiostat | 15 μL | An automated fast-flow/delayed paper-based platform for the simultaneous electrochemical detection of hepatitis B virus and hepatitis C virus core antigen | S. Boonkaew, A. Yakoh, N. Chuaypen, P. Tangkijvanich, S. Rengpipat, W. Siangproh and O. Chailapakul, Biosens. Bioelectron., 2021, 193, 113543 |
| SARS-CoV-2 | Human serum | Clinical sample | A | N.A. | Colorimetric | N.A. | 5 nM<br>(serum) | N.A. | 10 min | Yes<br>Multiple operations | (Blood separation)<br>Treated with sulfosuccinimidyl 2(biotinylthio) reagent<br>Pre-incubation | Mixing with reagent<br>Sample application<br>Buffer application<br>Reagent application<br>Imaging | Yes<br>HRP- protein<br>(immobilization protein<br>TMB | Monolular<br>Imager | 25 μL (off-chip)<br>80 μL (on-chip) | Vertical Flow Cellulose-Based Assays for SARS-CoV-2 Antibody Detection in Human Serum | S. Kim, Y. Hee, S. A. Miller, D. M. T. Tay, S. Yee, P. Kongsuphol, H. Jai, M. McBew, P. R. Perkan and H. D. Sikes, ACS Sens., 2021, 6, 1891-1898 |
| SARS-CoV-2 | Human serum | Clinical sample | A | N.A. | Colorimetric | N.A. | N.A.<br>99.5% accuracy | N.A. | <20 min | Yes<br>Multiple operations | (Blood separation) | Buffer application<br>Sample application<br>Buffer application<br>Changing top case<br>Reagent application<br>Detachment and imaging | Yes<br>AuNP- antibody | Plastic box<br>Smartphone | 40 μL | A Paper-Based Multiplexed Serological Test to Monitor Immunity against SARS-COV-2 Using Machine Learning | M. Brylewa, A. Gomchenko, D. R. Han, H.-A. Joung, Z. S. Ballard, R. Ghosh, Y. Zhang, D. Di Carlo and A. Ozcan, ACS Nano, 2024, 18, 16818-16831 |
| Cardiac troponin I (cTnI) | Human serum | Clinical sample | A | <40–4290 pg/mL | Colorimetric | ~100 ng/mL<br>(serum) | 0.2 pg/mL<br>(serum) | N.A. | <15 min | Yes<br>Multiple operations | (Blood separation) | Buffer application<br>Sample and reagent application<br>Buffer application<br>Changing top case<br>Reagent application<br>Detachment and imaging | Yes<br>AuNP- antibody<br>$NH_4CO_3$<br>$NH_4OH$ | Plastic box<br>Smartphone | 60 μL | Deep Learning-Enhanced Paper-Based Vertical Flow Assay for High-Sensitivity Troponin Detection Using Nanoparticle Amplification | G.-R. Han, A. Gomchenko, M. Brylewa, H.-A. Joung, R. Ghosh, G. Yim, N. Chang, M. Kim, K. Nga, M. Venugopal, K. Liao, O. B. Garner, D. Di Carlo and A. Ozcan, ACS Nano, 2024, 18, 27833–27845 |
| Cardiac troponin I (cTnI) | Human serum | Clinical sample | A | few-18 000 pg/mL | CL | 0.001–100 ng/mL<br>(serum) | 0.18 pg/mL<br>(serum) | N.A. | 20 min | Yes<br>Multiple operations | (Blood separation) | Buffer application<br>Sample and reagent application<br>Buffer application<br>Changing top case<br>Reagent application<br>Changing top case<br>Reagent application<br>CL imaging | Yes<br>AuNP-HRP-antibody<br>luminol<br>$H_2O_2$ | Plastic box<br>Portable reader | 60 μL | Deep Learning-Enhanced Chemiluminescence Vertical Flow Assay for High-Sensitivity Cardiac Troponin I Testing | G.-R. Han, A. Gomchenko, M. Brylewa, S. Yin, H.-A. Joung, R. Ghosh, S. Nga, A. Tomasula, Y. Lee, K. Nga, B. Mellon, O. B. Garner, D. Di Carlo and A. Ozcan, Small, 2023, 21, 2411588 |
| Anti-Borrelia burgdorferi antibody | Human serum | Clinical sample | A | N.A. | Colorimetric | N.A. | N.A.<br>Sensitivity 90.5%<br>Specificity 87.0%<br>(n = 90) | N.A. | <15 min | Yes<br>Multiple operations | (Blood separation) | Buffer application<br>Sample application<br>Change of top case<br>Buffer application<br>Deacetone<br>Imaging | No | 3D-printed cartridge<br>Smartphone | 20 μL | Point-of-Care Serodiagnostic Test for Early-Stage Lyme Disease Using a Multiplexed Paper-Based Immunoassay and Machine Learning | H.-A. Joung, Z. S. Ballard, J. Wu, D. K. Tseng, H. Teshome, L. Zhang, E. J. Horn, P. M. Arnuldo, N. J. Gallagher, O. B. Garner, D. Di Carlo and A. Ozcan, ACS Nano, 2020, 14, 229-240 |
| Anti-Borrelia burgdorferi antibody | Human serum | Clinical sample | A | N.A. | Colorimetric | N.A. | N.A.<br>Sensitivity 95.5%<br>Specificity 100.0% | Room temperature<br>>60 days<br>96% | <20 min | Yes<br>Multiple operations | (Blood separation) | Buffer and sample application<br>Changing top case<br>Reagent application<br>Detachment and imaging | Yes<br>AuNP- antibody | Plastic box<br>Smartphone | 20 μL | Rapid single-tier serodiagnosis of Lyme disease | R. Ghosh, H.-A. Joung, A. Gomchenko, B. Pulendrarajah, K. Nga, K. Pepperoni, N. Koudelstegen, B. J. Horn, O. B. Garner, E. Ghazali, A. O'Kula, P. M. Arnuldo, N. J. Gallagher, A. Ozcan and D. Di Carlo, Nat. Commun., 2024, 15, 7124 |
| Myoglobin | Human serum | Clinical sample | A | 8.6–75 ng/mL | FL | N.A. | 0.52 ng/mL<br>(serum) | N.A. | <15 min | Yes<br>Multiple operations | Blood separation<br>Pre-mix with antibody | Buffer application<br>Pre-mixing sample and reagent<br>Sample application<br>Buffer application<br>Removing top case<br>Inserting to phone reader<br>Imaging | Yes<br>AuNP-antibody | Plastic box<br>Smartphone<br>Light source and filter | 60 μL | Deep Learning-Enabled Multiplexed Point-of-Care Sensor using a Paper-Based Fluorescence Vertical Flow Assay | A. Gomchenko, H.-A. Joung, R. Ghosh, G.-R. Han, Z. S. Ballard, Q. Maloney, A. Bell, C. T. Z. Aung, O. B. Garner, D. D. Carlo and A. Ozcan, Small, 2023, 19, 2300617 |
| Creatine kinase-MB (CK-MB) | Human serum | Clinical sample | A | 1.1–23.4 ng/mL | FL | N.A. | 0.3 ng/mL<br>(serum) | N.A. | <15 min | Yes<br>Multiple operations | Blood separation<br>Pre-mix with antibody | Buffer application<br>Pre-mixing sample and reagent<br>Sample application<br>Buffer application<br>Removing top case<br>Inserting to phone reader<br>Imaging | Yes<br>AuNP-antibody | Plastic box<br>Smartphone<br>Light source and filter | 60 μL | Deep Learning-Enabled Multiplexed Point-of-Care Sensor using a Paper-Based Fluorescence Vertical Flow Assay | A. Gomchenko, H.-A. Joung, R. Ghosh, G.-R. Han, Z. S. Ballard, Q. Maloney, A. Bell, C. T. Z. Aung, O. B. Garner, D. D. Carlo and A. Ozcan, Small, 2023, 19, 2300617 |
| Heart-type fatty acid binding protein (FABP) | Human serum | Clinical sample | A | 1.3–43.7 ng/mL | FL | N.A. | 0.49 ng/mL<br>(serum) | N.A. | <15 min | Yes<br>Multiple operations | Blood separation<br>Pre-mix with antibody | Buffer application<br>Pre-mixing sample and reagent<br>Sample application<br>Buffer application<br>Removing top case<br>Inserting to phone reader<br>Imaging | Yes<br>AuNP-antibody | Plastic box<br>Smartphone<br>Light source and filter | 60 μL | Deep Learning-Enabled Multiplexed Point-of-Care Sensor using a Paper-Based Fluorescence Vertical Flow Assay | A. Gomchenko, H.-A. Joung, R. Ghosh, G.-R. Han, Z. S. Ballard, Q. Maloney, A. Bell, C. T. Z. Aung, O. B. Garner, D. D. Carlo and A. Ozcan, Small, 2023, 19, 2300617 |
| C-Reactive Protein (CRP) | Human serum | Diluted clinical sample | S | 0–10, 93.8 mg/L | Colorimetric | 0–10 mg/L<br>(serum) | N.A. | N.A. | <12 min | Yes<br>Multiple operations | (Blood separation)<br>10 times dilution with buffer | Buffer application<br>Sample and reagent application<br>Running buffer<br>Deacetone<br>Imaging | Yes<br>AuNP-antibody | 3D-printed cartridge<br>Smartphone | 60 μL | Deep learning-enabled point-of-care sensing using multiplexed paper-based sensors | Z. S. Ballard, H.-A. Joung, A. Gomchenko, J. Liang, K. Nugroho, D. Di Carlo, O. B. Garner and A. Ozcan, NPJ Digit. Med., 2020, 3, 66 |
| Anti-interferency autoantibodies (anti-PR3 Abs) | Human serum | Diluted clinical sample | S | 111.09–1937.42 μg/mL | Colorimetric | 0.033–3 μg/mL<br>(PBS) | 0.001 μg/mL (smartphone)<br>0.03 μg/mL (naked eye)<br>(PBS) | N.A. | <10 min | No<br>>10 min | (Blood separation)<br>100-fold dilution with PBS | Sample and buffer application<br>Imaging | No | (Smartphone) | 20 μL | One-Step Gold Nanoparticle Signal Amplification in a 3D Paper-Based Device for Rapid Detection of Anti-Interferency Autoantibodies | Y.-G. Chen, U.-I. Wu, Y.-H. Pan and C.-F. Chen, Biosens. Bioelectron., 2025, 287, 117724 |
| SARS-CoV-2 | Human saliva | Spiked into biofluid sample | 2 | 10–100 μg/mL | Colorimetric | 10–100 μg/mL<br>(saliva) | 10 μg/mL<br>(saliva) | N.A. | 8 min | Yes<br>Multiple operations | No | Reagent application<br>Sample application<br>Centrifugation for 5 times<br>Imaging | Yes<br>AuNP-antibody | Centrifuge<br>Black box<br>Smartphone | 25 μL | μPADs on Centrifuge Microfluidic Discs for Rapid Sample-to-Answer Salivary Diagnostics | S. Liu, Y. Hou, Z. Li, C. Yang and D. Liu, ACS Sens., 2020, 5, 3020-3029 |
| Cardiac troponin I (cTnI) | Human whole blood | Spiked into biofluid sample | 2 | 50 pg/mL–50 ng/mL | Eschem (EIS) | 50 pg/mL to 50 ng/mL<br>(artificial blood plasma) | 4.6 pg/mL (730 fM)<br>(artificial blood plasma) | N.A. | 65 min | Yes<br>Multiple operations | No | Folding and sample application<br>Plating and buffer application<br>Detaching<br>Peeling off and folding paper<br>Reagent application<br>Eschem measurement | Yes<br>$Fe(CN)_6^{3-/4-}$ | Potentiostat | 20 μL | Paper-Based All-in-One Organ Nanosensor for Point-of-Care Detection of Cardiac Protein Markers in Whole Blood | H. Hu, Z. Qin, X. Li, Y. Pan, H. Xu, P. Pan, P. Song and X. Liu, ACS Sens., 2023, 8, 3974-3984 |
| Brain natriuretic peptide (BNP) | Human whole blood | Spiked into biofluid sample | 2 | 8 pg/mL–8 ng/mL | Eschem (EIS) | 8 pg/mL to 8 ng/mL<br>(artificial blood plasma) | 1.2 pg/mL (50 fM)<br>(artificial blood plasma) | N.A. | 65 min | Yes<br>Multiple operations | No | Folding and sample application<br>Plating and buffer application<br>Detaching<br>Peeling off and folding paper<br>Reagent application<br>Eschem measurement | Yes<br>$Fe(CN)_6^{3-/4-}$ | Potentiostat | 20 μL | Paper-Based All-in-One Organ Nanosensor for Point-of-Care Detection of Cardiac Protein Markers in Whole Blood | H. Hu, Z. Qin, X. Li, Y. Pan, H. Xu, P. Pan, P. Song and X. Liu, ACS Sens., 2023, 8, 3974-3984 |
| D-Dimer | Human whole blood | Spiked into biofluid sample | 2 | 91 ng/mL–91 μg/mL | Eschem (EIS) | 91 ng/mL to 91 μg/mL<br>(artificial blood plasma) | 149 pg/mL (730 fM)<br>(artificial blood plasma) | N.A. | 65 min | Yes<br>Multiple operations | No | Folding and sample application<br>Plating and buffer application<br>Detaching<br>Peeling off and folding paper<br>Reagent application<br>Eschem measurement | Yes<br>$Fe(CN)_6^{3-/4-}$ | Potentiostat | 20 μL | Paper-Based All-in-One Organ Nanosensor for Point-of-Care Detection of Cardiac Protein Markers in Whole Blood | H. Hu, Z. Qin, X. Li, Y. Pan, H. Xu, P. Pan, P. Song and X. Liu, ACS Sens., 2023, 8, 3974-3984 |
| HIV1 | Pseudo whole blood | Spiked into biofluid sample | 2 | 50–150 nM | BL | N.A. | 2.8 nM<br>(pooled serum) | Capped vials with argon, silica gel<br>-20 °C<br>~3 months | 21 min | No<br>21–30 min* | No | Sample application<br>Imaging | No | Camera<br>Box | 30–60 μL | Paper-Based Antibody Detection Devices Using Bioluminescent BRET-Switching Sensor Proteins | K. Tendia, B. Van Geneen, R. Arik, Y. Hinde, M. Merka and D. Citkins, Angew. Chem. Int. Ed., 2018, 57, 15369-15373 |
| Hemagglutinin (HA) | Pseudo whole blood | Spiked into biofluid sample | 2 | 50–150 nM | BL | N.A. | 7.1 nM<br>(pooled serum) | Capped vials with argon, silica gel<br>-20 °C<br>~3 months | 21 min | No<br>21–30 min* | No | Sample application<br>Imaging | No | Camera<br>Box | 30–60 μL | Paper-Based Antibody Detection Devices Using Bioluminescent BRET-Switching Sensor Proteins | K. Tendia, B. Van Geneen, R. Arik, Y. Hinde, M. Merka and D. Citkins, Angew. Chem. Int. Ed., 2018, 57, 15369-15373 |
| Dengue virus type 1 (DEN1) | Pseudo whole blood | Spiked into biofluid sample | 2 | 50–150 nM | BL | N.A. | 16.3 nM<br>(pooled serum) | Capped vials with argon, silica gel<br>-20 °C<br>~3 months | 21 min | No<br>21–30 min* | No | Sample application<br>Imaging | No | Camera<br>Box | 30–60 μL | Paper-Based Antibody Detection Devices Using Bioluminescent BRET-Switching Sensor Proteins | K. Tendia, B. Van Geneen, R. Arik, Y. Hinde, M. Merka and D. Citkins, Angew. Chem. Int. Ed., 2018, 57, 15369-15373 |
| Hepatitis B virus (HBV) | Pseudo whole blood | Spiked into biofluid sample | 2 | 0.035–200 mg/mL | FL | N.A. | 2.6 ng/mL<br>(pooled whole blood) | Wrapped with reagent paper in aluminum bag with a silica gel pack<br>-20 °C<br>~90 days<br>>90% | 65 min | Yes<br>Multiple operations | No | Sample application<br>Folding and buffer application<br>Folding and buffer application<br>Peeling off and folding<br>Buffer application<br>Detaching<br>FL measurement | No | Smartfone<br>Fluorescence medical platform | 5 μL | Origami Paper-Based Immunoassay Device with CRISPR/Cas12a Signal Amplification | H. Suzuki, G. Tang, P. Nath, Y. Hecht and D. Citkins, ACS Sens., 2025, 10, 1811-1821 |
| HIV-1 | Human plasma | Spiked into biofluid sample | 2 | 0–30 ng/mL | Colorimetric | 0.03–3 ng/mL<br>(plasma) | 0.03 ng/mL<br>(plasma) | N.A. | <10 min | Yes<br>(color timer on device) | Blood separation | Sample application<br>Folding device and buffer application<br>Folding device and reagent application<br>Imaging | Yes<br>TMB | (Smartphone) | 3 μL | An electricity- and instrument-free infectious disease sensor based on a 3D origami paper-based analytical device | C.-A. Chen, H. Yuan, C.-W. Chen, Y.-S. Chen, W.-H. Sheng and C.-F. Chen, Lab Chip, 2021, 21, 1908-1915 |
| α-Fetoprotein | Human serum | Spiked into biofluid sample | 2 | 0.1–100 ng/mL | Eschem (EIS) | 0.01–500 ng/mL (9 min)<br>0.5 pg/mL to 10 ng/mL (30 min) | 1.69 pg/mL (9 min)<br>0.56 fg/mL (30 min) | 4 °C<br>>13 days<br>106% | 9 min<br>30 min | Yes<br>Multiple operations | (Blood separation) | Sample and buffer application<br>Device rotation for 5 times<br>Eschem measurement | No | Potentiostat | 20 μL | Hand-Operated, Paper-Based Rotational Vertical Flow Immunosensor for the Impedimetric Detection of α-Fetoprotein | A. Yakoh, B. Mehmeti, K. Kaloker and S. Chaiyo, Anal. Chem., 2022, 94, 5893-5900 |
| Procalcitonin | Synthetic serum | Spiked into artificial biofluid sample | 1 | 2–10 μg/mL | AR | 2–100 μg/mL<br>(serum) | 2 μg/mL<br>(serum) | N.A. | 84 min | Yes<br>Multiple operations | (Blood separation)<br>Pre-mix with anti-target antibody | Pre-incubation<br>Sample application<br>Washing<br>Reagent application<br>Washing for three times<br>Imaging | Yes<br>Biotin-antibody<br>Streptavidin-AuNP | Smartphone | 1 μL | A Robust and User-Friendly Alternative to Densitometry Using Origami Biosensors and Digital Logic | B. M. Russell, A. Abia-Patiño, M. Borges and R. de la Rica, ACS Sens., 2019, 4, 1712-1718 |
| α-fetoprotein | Buffer | N.A. | - | N.A. | Eschem (ZA) | 10–100 ng/mL<br>($KNO_3$) | 0.03 ng/mL<br>($KNO_3$) | N.A. | 33 min | Yes<br>Multiple operations | N.A. | Sample application<br>Washing<br>Reagent application<br>Washing<br>Eschem measurement | Yes<br>$Fe(CN)_6^{3-/4-}$ | Potentiostat | 1 μL | 3D Capillary-Driven Paper-Based Sequential Microfluidic Device for Electrochemical Sensing Applications | A. Yakoh, S. Chaiyo, W. Siangproh and O. Chailapakul, ACS Sens., 2019, 4, 1211-1221 |
| Plasminogen activator inhibitor-type plasminogen activator inhibitor-type plasminogen activator inhibitor-type