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(54) **SYSTEMS AND METHODS FOR RAPID PATHOGEN DETECTION**

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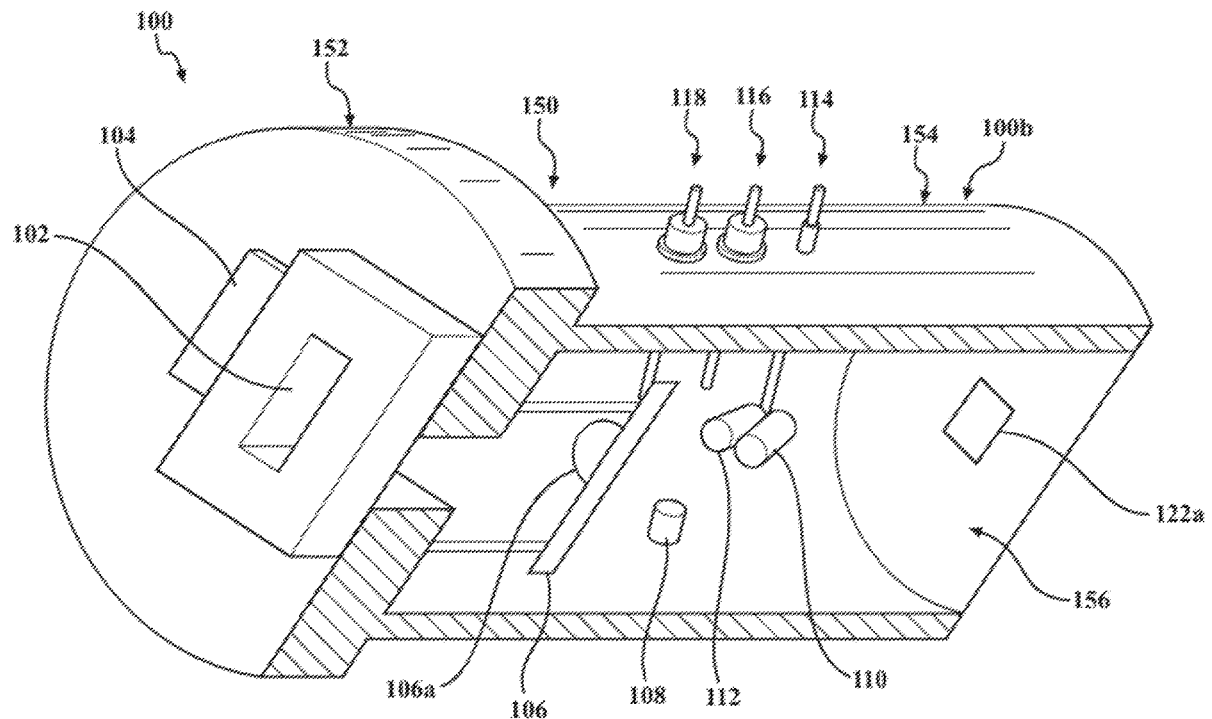
(57) **ABSTRACT**

(22) Filed: **Aug. 31, 2023**

A device for detecting pathogens comprises a chamber configured to receive a sample including an analyte and a matrix, a gas inlet extending into the chamber and configured to adjust the pressure within the chamber to ionize the volatile or non-volatile molecules of the sample, an ion mobility spectrometer configured to obtain the ionized molecules of the sample to obtain pathogen data, and a computing device configured to analyze the pathogen data to determine one or more pathogens of the analyte.

**Related U.S. Application Data**

(60) Provisional application No. 63/374,172, filed on Aug. 31, 2022.



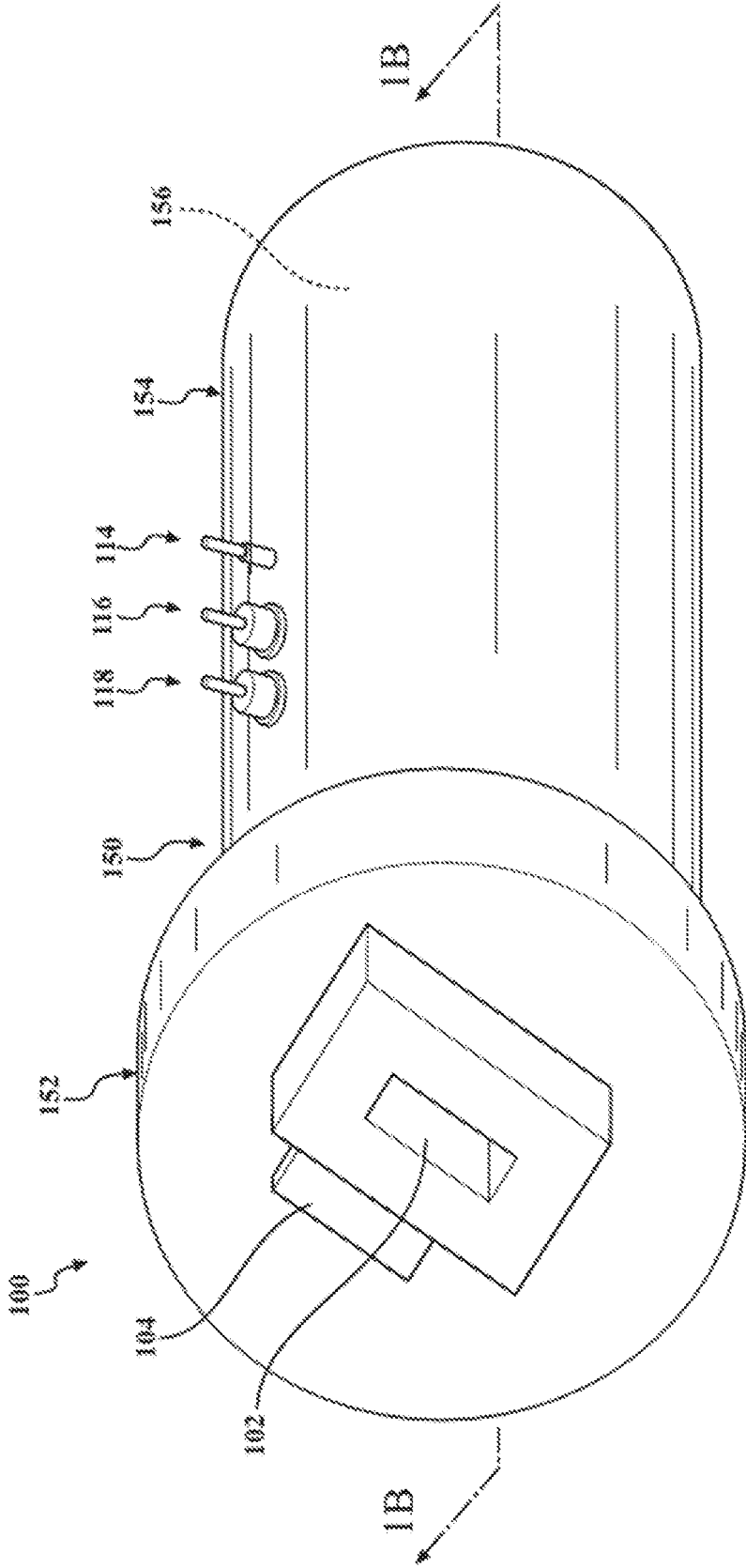


FIG. 1A

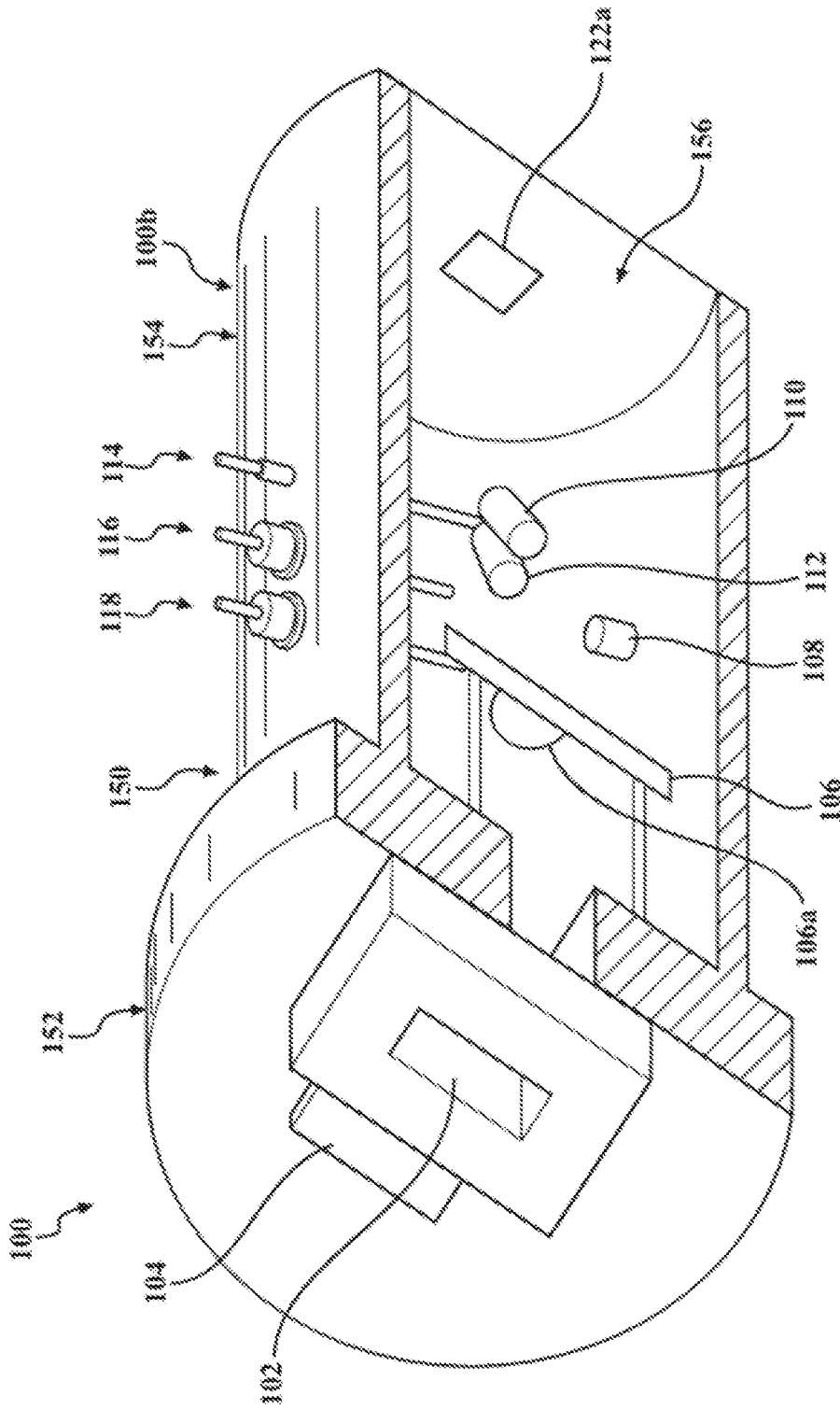


FIG. 1B

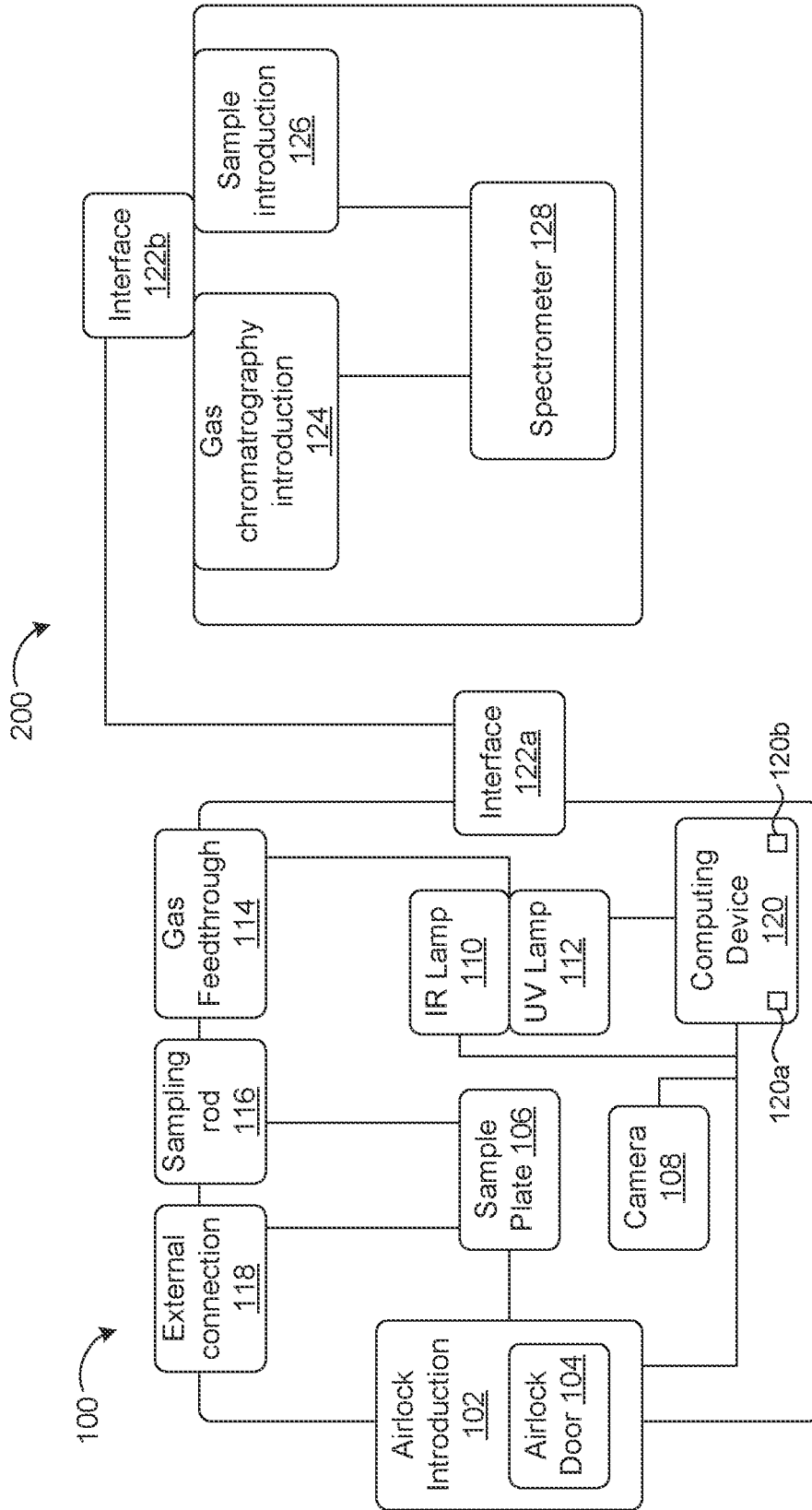


FIG. 2A

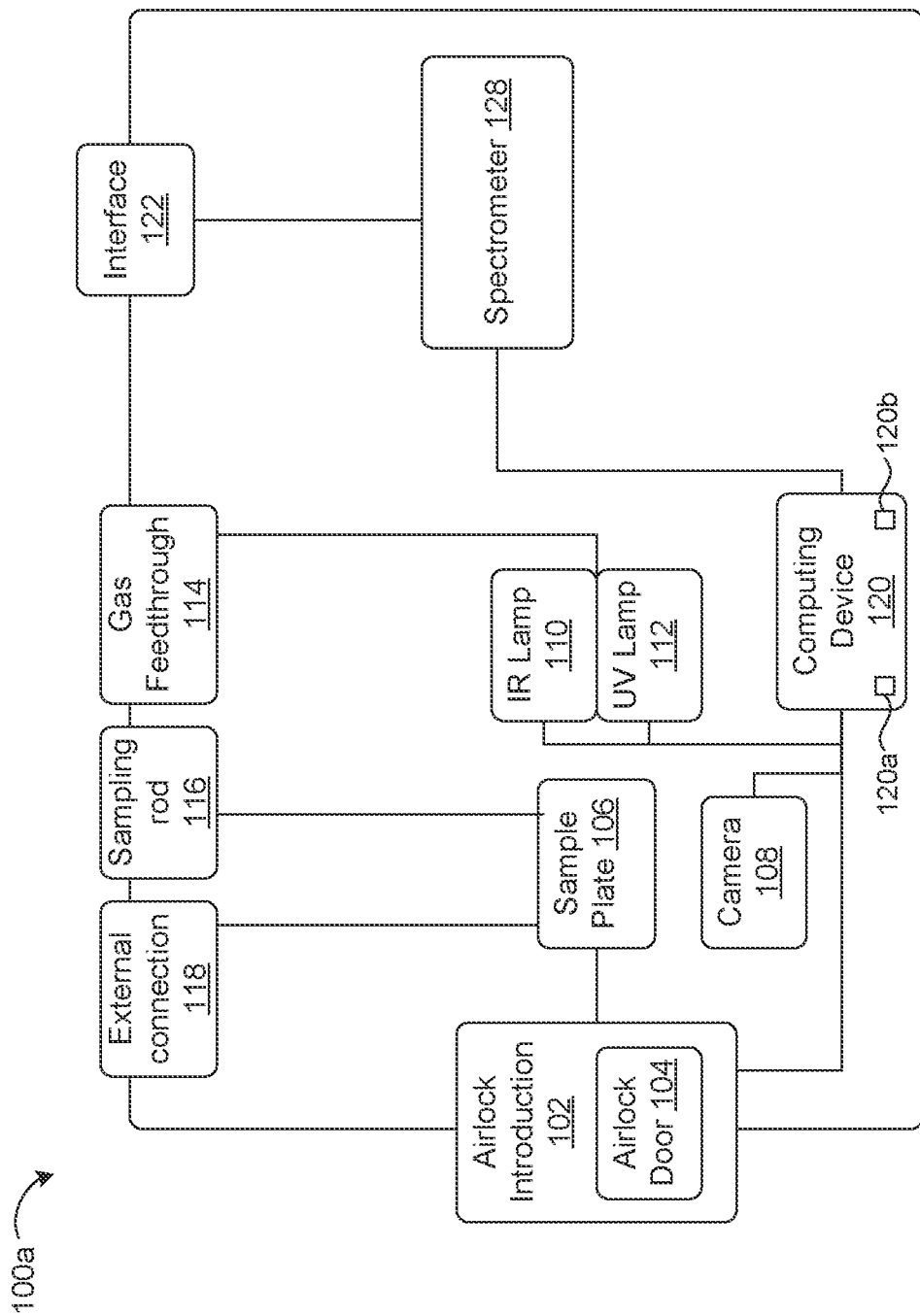


FIG. 2B

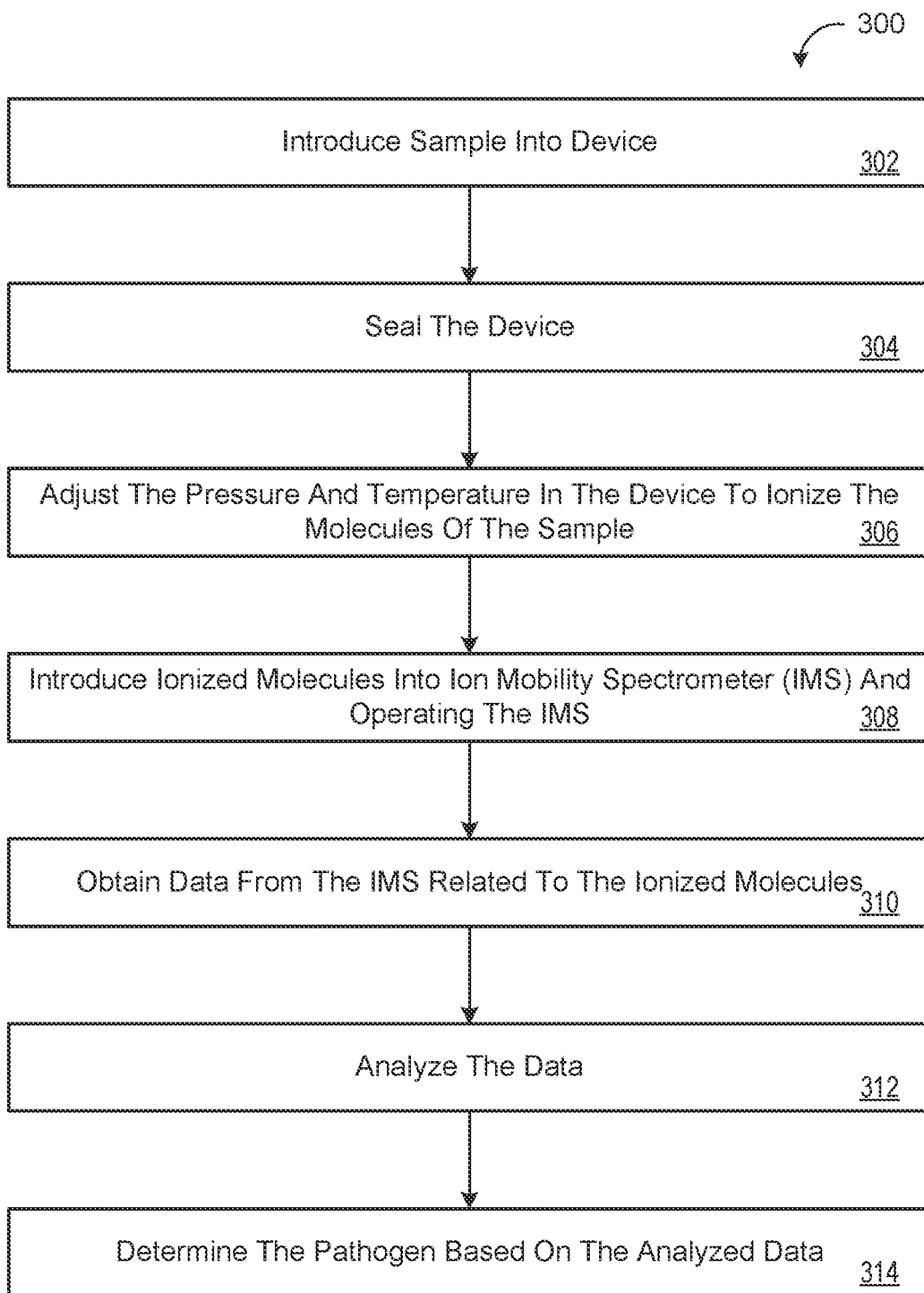


FIG. 3

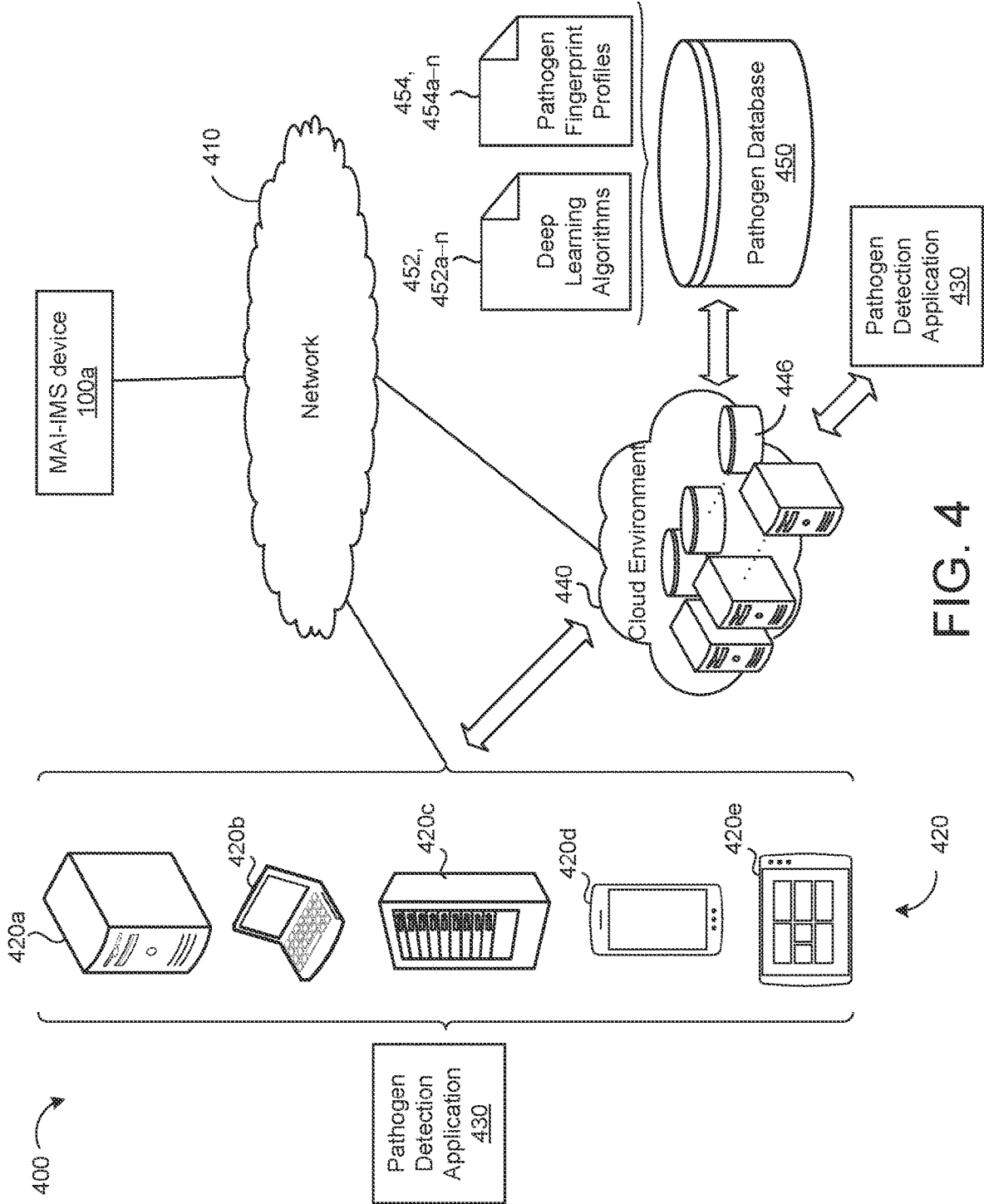


FIG. 4

## SYSTEMS AND METHODS FOR RAPID PATHOGEN DETECTION

### CROSS REFERENCE TO RELATED APPLICATIONS

**[0001]** This U.S. patent application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application 63/374, 172, filed on Aug. 31, 2022. The disclosure of this prior application is considered part of the disclosure of this application and is hereby incorporated by reference in its entirety.

### TECHNICAL FIELD

**[0002]** This disclosure relates to systems and methods for rapid microorganism, environmental toxin, or pathogen detection.

### BACKGROUND

**[0003]** Today, the global population's accessibility to transportation connectivity has increased the mobility of people and, as a result, the mobility of pathogen-related infections. The COVID-19 pandemic highlighted many issues with the global biodefense infrastructure, and the lack of rapid pathogen identification played a significant role in the spread of COVID-19. Some of these issues include struggling or failing to provide rapid onsite pathogen identifications, and, instead, many agencies and entities rely on slow and costly offsite testing, business shutdowns, and mass-scale quarantines, which could indirectly be a factor in infection proliferation. Thus, a reliable, rapid onsite pathogen screening is needed to respond quickly to pathogen outbreaks or biological warfare agent incidents efficiently.

### SUMMARY

**[0004]** One aspect of the disclosure provides a device for detecting pathogens comprising a chamber configured to receive a sample including an analyte and a matrix, a gas inlet extending into the chamber and configured to adjust the pressure within the chamber to ionize the molecules of the sample, an ion mobility spectrometer configured to obtain the ionized molecules of the sample to obtain pathogen data, and a computing device configured to analyze the pathogen data to determine one or more pathogens of the analyte.

**[0005]** Implementations of the disclosure may include one or more of the following optional features. In some implementations, the device further comprises a housing configured to house the chamber, the ion mobility spectrometer, and the computing device. The housing may be configured to be handheld.

**[0006]** The device may further comprise a heat source within the chamber configured to adjust the temperature within the chamber.

**[0007]** The computing device may analyze the pathogen data using artificial intelligence, which may include deep learning algorithms to improve the robustness of the analysis of the pathogen data.

**[0008]** The device may further comprise an airlock door configured to selectively permit access to the chamber. The device may further comprise a sampling rod configured to selectively transmit the sample into the chamber.

**[0009]** Another aspect of the disclosure provides a system for detecting pathogens comprising a pathogen detection device comprising a chamber configured to receive a sample

including an analyte and a matrix, a gas inlet extending into the chamber and configured to adjust the pressure within the chamber to ionize the molecules of the sample, an ion mobility spectrometer configured to obtain the ionized molecules of the sample to obtain pathogen data, and an external computing device in communication with the pathogen detection, the external computing device configured to analyze the pathogen data to determine one or more pathogens of the analyte.

**[0010]** This aspect may include one or more of the following optional features. In some implementations, the external computing device is one of a smartphone, a laptop computer, a desktop computer, or a tablet computer.

**[0011]** The pathogen detection device may be in communication with the external computing device via a wireless telecommunication network.

**[0012]** The external computing device may include data processing hardware and memory hardware in communication with the data processing hardware, the memory hardware storing instructions that when executed on the data processing hardware cause the data processing hardware to perform operations to analyze the pathogen data to determine one or more pathogens of the analyte. The operations may include analyzing the pathogen data using artificial intelligence.

**[0013]** The external computing device may be in communication with cloud computing resources storing a pathogen database including a plurality of deep learning algorithms and a plurality of pathogen fingerprint profiles.

**[0014]** Another aspect of the disclosure provides a method for detecting pathogens comprising introducing a sample into a pathogen detection device, adjusting the pressure and temperature within the pathogen detection device to ionize the molecules of the sample, introducing the ionized molecules of the sample into an ion mobility spectrometer, operating the ionized mobility spectrometer, obtaining pathogen data from the ionized mobility spectrometer related to the ionized molecules of the sample, analyzing the pathogen data, and determining at least one pathogen of the sample based on the analysis of the pathogen data.

**[0015]** The pathogen detection device and the ion mobility spectrometer may be contained within the same housing.

**[0016]** The pressure within the pathogen detection device may be adjusted via a gas inlet into the pathogen detection device.

**[0017]** The method may further comprise adjusting the temperature within the pathogen detection device via one of an ultraviolet lamp or an infrared lamp.

**[0018]** The pathogen data may be analyzed using artificial intelligence. The pathogen data may be analyzed using one or more deep learning algorithms to improve the robustness of the analysis of the pathogen data.

**[0019]** The details of one or more implementations of the disclosure are set forth in the accompanying drawings and the description below. Other aspects, features, and advantages will be apparent from the description and drawings, and from the claims.

### DESCRIPTION OF DRAWINGS

**[0020]** Reference will now be made to the accompanying Figures, which are not necessarily drawn to scale, and wherein:



**[0021]** FIG. 1A is a perspective view of an exemplary matrix-assisted ionization (MAI) device in accordance with principles of the present disclosure;

**[0022]** FIG. 1B is a cross-sectional perspective view of the MAI device of FIG. 1A, taken along lines 1B-1B;

**[0023]** FIG. 2A is a schematic view of the MAI device of FIG. 1A and an exemplary ion mobility spectrometry (IMS) device in accordance with principles of the present disclosure;

**[0024]** FIG. 2B is a schematic view of an exemplary MAI-IMS device which incorporates the MAI device of FIGS. 1A-1B and the IMS device of FIG. 2A;

**[0025]** FIG. 3 is a method for use of the MAI-IMS device of FIG. 2B;

**[0026]** FIG. 4 is a schematic view of a system including the MAI-IMS device of FIG. 2B.

**[0027]** Like reference symbols in the various drawings indicate like elements.

#### DETAILED DESCRIPTION

**[0028]** Some implementations of the disclosed technology will be described more fully with reference to the accompanying drawings. This disclosed technology may, however, be embodied in many different forms and should not be construed as limited to the implementations set forth herein.

**[0029]** Referring to FIGS. 1A-1B, a matrix-assisted ionization (MAI) device **100** is generally shown. In some implementations, the MAI device **100** may interface with (or retrofit) an ion mobility spectrometry (IMS) device **200**, as shown in FIG. 2A. In other implementations, as shown in FIG. 2B, an MAI-IMS device **100a** may incorporate the MAI device **100** of FIGS. 1A-1B and the IMS device **200** of FIG. 2A.

**[0030]** The MAI device **100** may use a mixture of an analyte and a matrix in solution and may not require a laser. To ionize the analyte, the MAI device **100** may apply a pressure differential and specific matrix to the solution, spontaneously converting all classes of volatile and non-volatile biomolecules to gas-phase ions. In some implementations, the matrix may include any suitable solvent, such as 2-aminobenzyl alcohol, anthranilic acid, 2-hydroxyacetophenone, 1,1-Dimethylpyrrolidine-2,5-dione (DMPD), 1,2-Dicyanobenzene (1,2-DCB), 1,5-Diaminonaphthalene (1,5-DAN), 1,5-Naphthalenediamine (1,5-ND), 2-Amino-5-nitropyridine (2A5NP), 2,4-Dihydroxybenzylamine (DHBAm), 2,4,6-Trihydroxyacetophenone (THAP), 2,5-Dihydroxybenzoic acid (DHB), 2,5-Dihydroxybenzylamine (DHBA), 2,6-Dihydroxyacetophenone (DHAP), 3-Hydroxypicolinic acid (3-HPA), 3-Nitrobenzotrile (3-NBN), 3,4-Dihydroxybenzaldehyde (3,4-DHBA), 4-Nitroacetanilide (4-NAA), 6-Aminoquinoline (6-AQ), 6-Aza-2-thiothymine (ATT), 7-Azaindole (7AI), 7,7,8,8-Tetracyanoquinodimethane (TCNQ), 9-Aminoacridine (9-AA), 9,10-Dihydroxyanthracene (DHA), Benzoyl chloride (BzCl), Bis(dimethylamino)naphthalene (DMAN), Cinnamic Acid Derivatives, Dihydroxybenzoic acid (DHB), Ferulic acid, Ferulic Acid (FA), Nitroaromatic Compounds, p-Nitroaniline (pNA), Sinapinic acid (SA), or  $\alpha$ -Cyano-4-hydroxycinnamic acid (CHCA). Accordingly, the MAI device **100** may require less power input demand than other systems as it does not require high voltages or lasers for ionization.

**[0031]** The MAI device **100** may allow for the ionization of small and large biologically relevant molecules, such as lipids, peptides, proteins, deoxyribonucleic acids, ribo-

nucleic acids, carbohydrates, metabolites, or their derivatives, etc., to produce a molecular fingerprint of a microorganism or environmental toxin. The ionization by the MAI device **100** may include reduced in-source fragmentation products, which may be referred to as a soft ionization technique, and which may allow the MAI device **100** to analyze delicate molecules.

**[0032]** The IMS device **200** may be relatively compact, portable, and widely available. The gas-phase ionization of the IMS device **200** may occur by bombarding volatile molecules with high-energy electrons from Ni beta-rays. The IMS device **200** may create an electric field that transfers the ions into a drift tube filled with an inert gas. The IMS device **200** may separate and identify gas-phase ions based on their gas collisions rates calculated from mobility, size, and mass-to-charge ratio.

**[0033]** In some implementations, the IMS device **200** may include, or be coupled with, multi-capillary columns (MCC-IMS) to increase the resolution and provide a 2D mobility plot. In such implementations, the IMS device **200** may provide an orthogonal dimension of separation to increase the resolution. In other implementations, the IMS device **200** may use Helium in the drift gas mixture to increase the resolution of complex mixtures for biomolecular analyses. In yet other implementations, the IMS device **200** may be a trapped ion mobility spectrometry (TIMS) to increase resolution.

**[0034]** The MAI-IMS device **100a** combines MAI and IMS to allow for spontaneously converting all classes of volatile and nonvolatile biomolecules to gas-phase ions. The MAI-IMS device **100a** may receive a sample of interest **106a** mixed with an MAI matrix and create a differential pressure region (e.g., atmospheric pressure (AP) to vacuum pressure), promoting sublimation of the sample **106a**, i.e., matrix mix producing gas-phase ions. The pressure differential in the MAI-IMS device **100a** may cause disruptions in the sample **106a**, i.e., matrix crystals resulting in matrix sublimation causing micro “explosions” due to the reduced surface area from the matrix converting to the gas-phase ions. This may result in a charge separation process, e.g., fracto/triboluminescence, which is the release of energy from the breaking of crystals, so that particles are displaced into the gas phase having an excess positive or negative charge. Therefore, an external energy source (via laser, voltage, electronics, or other bulky, expensive equipment) may not be needed for ionization to occur.

**[0035]** Referring to FIGS. 1A and 1B, the MAI device **100** may include a housing **150** having an introduction portion **152** and a body portion **154**, the body portion **154** defining an interior chamber **156**. The housing **150** may be formed from any suitable metal, such as steel, iron, stainless steel, etc., or plastic, such as polyethylene terephthalate, low or high density polyethylene, polyvinyl chloride, polypropylene, bisphenol A, etc. The housing **150** shown in FIGS. 1A and 1B is exemplary only, and it should be understood that the housing **150** may include any suitable shape and configuration. In some implementations, the housing **105** may be designed to be handheld, e.g., it may be less than the size of a traditional textbook.

**[0036]** The MAI device **100** includes an airlock introduction port **102** including an airlock door **104**. The airlock door **104** may be automatically operated or manually operated. The airlock introduction **102** facilitates access to a sample plate **106** in the chamber **156** that is configured to receive the

sample **106a**, which includes an analyte of interest and any suitable matrix, as set forth above. In some implementations, the sample **106a** may be introduced into the MAI device **100** via a matrix mix inserted into the MAI device **100**, or via a sampling rod **116**. In implementations where the sample rod **116** is used to introduce the sample **106a**, a swab, a test strip, or other suitable mechanism may be used to facilitate introduction of the sample **106a** into the device **100**. In some implementations, the swab or strip may be reusable.

[0037] The MAI device **100** may include a camera **108**, an infrared (IR) lamp **110**, and an ultraviolet (UV) lamp **112** in the chamber **156**. The camera **108** may be a high-speed camera or any other suitable camera. The camera **108** may provide a live video feed to a user (e.g., an electronic device of the user as set forth below) of the sample **106a** to ensure that the sample **106a** is being ionized and that the sample **106a** is at the correct location.

[0038] The IR lamp **110** and the UV lamp **112** are configured to adjust the heat in the MAI **100** to desired levels. In some implementations, the IR lamp **110** and the UV lamp **112** may adjust the temperature of the chamber **156** to between approximately 40° C. and 150° C. The MAI device **100** includes a gas feedthrough **114** configured to adjust the inert or other suitable gas pressure in the MAI device **100** to desired levels. In some implementations, the gas feedthrough **114** may adjust the pressure in the chamber **156** to between approximately  $1.0 \times 10^{-3}$  torr and  $1.0 \times 10^3$  torr. The gas feedthrough **114** may receive external gas connections to modify the pressure within the MAI device **100**. Additionally, the MAI device **100** may include an external connection **118** to facilitate any additional connections as desired. For example, the external connection **118** may be configured to receive electronic devices, voltage applications, or any other suitable external connection.

[0039] The MAI device **100** may separate and concentrate pathogens of the sample **106a** by electrokinetic concentration, which, in some implementations, may perform isolation and concentration of bacteria in approximately three minutes, and the density factor may be increased nearly a thousand-fold in a local area of approximately  $5000 \mu\text{m}^2$  from a low bacteria concentration of  $5 \times 10^3$  CFU/ml. In some implementations, the MAI device **100** may be connected with capillary electrophoresis (CE) systems, microfluidic devices, lab-on-a-chip systems, ion-selective membrane devices, electrochemical sensors, field-flow fractionation, electrophoretic devices, etc.

[0040] The MAI device **100** may include a computing device **120** including data processing hardware **120a** (e.g., a computing device that executes instructions) and memory hardware **120b**. The memory hardware **120b** is in communication with the data processing hardware **120a** and the memory hardware **120b** stores instructions that are executed by the data processing hardware **120a**. For example, the data processing hardware **120a** may execute instructions that control one or more of the electromechanical devices of the MAI device **100**, including, but not limited to the airlock introduction **102**, the airlock door **104**, the sample plate **106**, the camera **108**, the IR lamp **110**, the UV lamp **112**, the gas feedthrough **114**, the sampling rod **116**, the external connection **118**, and a spectrometer **128** (for the MAI-IMS device **100a**).

[0041] Referring to FIGS. 1A-1B and 2A, the MAI device **100** may be in communication with the IMS device **200** via a first interface **122a** in the MAI device **100** and a second

interface **122b** in the IMS device **200**. For example, the IMS device **200** may include the spectrometer **128**, a sample introduction **126**, and a gas or liquid chromatography introduction **124**. In some implementations, the sample **106a** may pass through a liquid chromatography system before the sample **106a** is introduced into the MAI device **100**. In some implementations, the sample **106a** may pass through a gas chromatography system before the sample **106a** is introduced into the IMS device **200**. The second interface **122b** may receive the sample **106a** from the first interface **122a**. Such transmission of the sample **106a** may be performed automatically via any suitable means, i.e., mechanical, electro-mechanical, etc., or the transmission may be performed manually, e.g., by a user. The first interface **122a** may be an ion gate that opens and closes to allow gas ions to flow into the spectrometer **128** via the combination of carrier gas and electric field from a low voltage extraction of the ion optic focusing.

[0042] Referring to FIG. 2B, the MAI-IMS device **100a** may incorporate the spectrometer **128** within the confines of device **100a** itself. The foregoing description of the MAI device **100** and the IMS device **200** as two separate components, may equally apply to the MAI-IMS device **100a** as one single component. In some implementations, the MAI-IMS device **100a** may receive the sample **106a** through the airlock door **104** or the sampling rod **116**, and then, after ionization, the gas ions of the sample **106a** may be introduced to the spectrometer **128** via the interface **122**. In other implementations, the sample **106a** may be introduced to the MAI-IMS device **100a** via the airlock door **104** or the sampling rod **116**, and then, after ionization is complete, the ionized gas molecules of the sample **106a** may be automatically transferred to the spectrometer **128**.

[0043] The spectrometer **128** may use any suitable analysis, such as drift tube IMS, low pressure drift tube IMS, travelling wave IMS, trapped IMS, high-field asymmetric waveform IMS, differential mobility analyzer, etc., to determine MAI-IMS data related to the ionized gas molecules of the sample **106a**. The computing device **120** may obtain the MAI-IMS data from the spectrometer **128** to obtain a molecular fingerprint of the microorganism(s) of the sample **106a** and determine the pathogen(s) and other microorganisms of the sample **106a**.

[0044] In some implementations, the MAI-IMS device **100a** may be in communication with an external computing device **420**, such as a standard server **320a**, as a laptop computer **320b**, as part of a rack server system **320c**, as a mobile device **320d** (such as a smartphone), or as a tablet computer **320e**, etc., such that the computing device **120** resides in one or more of the external computing devices **420**. For example, the MAI-IMS device **100a** may be incorporated into a smartphone case and is in communication with the smartphone contained in the case (e.g., wired or wireless connection), wherein the smartphone includes the computing device **120** that performs one or more of the functions described above.

[0045] Referring to FIG. 3, a method **300** for operating the MAI-IMS device **100a** is generally shown. At step **302**, the sample **106a** is introduced into the chamber **156** of the MAI-IMS device **100a**, e.g., via the airlock door **104** and/or the sampling rod **116**. At step **304**, the MAI-IMS device **100a** is sealed, e.g., by closing and sealing the airlock door **104**. At step **306**, the IR lamp **110** and the UV lamp **112** adjust the heat within the chamber **156** to the desired

temperature and the gas feedthrough **114** and/or the external connection **118** adjust the pressure within the chamber **156** to the desired temperature to ionize the molecules of the sample **106a**. In some implementations, no heat is required.

[0046] At step **308**, the ionized molecules are transmitted to the ion mobility spectrometer **128** and the ion mobility spectrometer **128** is operated by the ionized molecules being accelerated through a drift field to a detector. At step **310**, the computing device **120** obtains the MAI-IMS data from operation of the ion mobility spectrometer **128**. At step **312**, the computing device **120** analyzes the MAI-IMS data. Such analysis may include comparing the MAI-IMS data to pathogen fingerprint profiles **454**, **454a-n**, implementing artificial intelligence such as conducting one of the deep learning algorithms **452**, **452a-n**, or any other suitable analysis. At step **314**, the computing device **120** determines the pathogen based on the analyzed MAI-IMS data.

[0047] Referring to FIG. 4, a system **400** for implementing the MAI-IMS device **100a** is generally shown. The system **400** may include a network **410** which provides access to cloud computing resources **440** (e.g., distributed system) for providing access to a pathogen database **450**. The system **400** may include a pathogen detection application **430** that may be executed by a number of different devices **420**, including a standard server **420a**, as a laptop computer **420b**, as part of a rack server system **420c**, as a mobile device **420d** (such as a smartphone), or as a tablet computer **420e**. In some implementations, all or a portion of the pathogen detection application **430** may be executed by the cloud computing resources **440**. The pathogen detection application **430** may be configured to obtain and analyze data from the MAI-IMS device **100a** in order to determine whether the sample **106a** includes any pathogens, which pathogens the sample **106a** may include, origin of the pathogen, variant and strain analysis, etc.

[0048] The network **410** may include any type of network that allows sending and receiving communication signals, such as a wireless telecommunication network, the Internet, a cellular telephone network, a time division multiple access (TDMA) network, a code division multiple access (CDMA) network, Global system for mobile communications (GSM), a third generation (3G) network, fourth generation (4G) network, fifth generation (5G) network, a satellite communications network, and other communication networks. The network **410** may include one or more of a Wide Area Network (WAN), a Local Area Network (LAN), and a Personal Area Network (PAN). In some examples, the network **410** includes a combination of data networks, telecommunication networks, and a combination of data and telecommunication networks. The MAI-IMS device **100a**, the device **420** (including the pathogen detection application **430**), and the pathogen database **450** communicate with each other by sending and receiving signals (wired or wireless) via the network **410**, which, in some examples, may utilize Bluetooth, Wi-Fi, etc. In some examples, the network **410** provides access to cloud computing resources, which may be elastic/on-demand computing and/or storage resources **446** available over the network **410**. The term “cloud” services generally refers to a service delivered from one or more remote devices accessible via one or more networks **410**, rather than a service performed locally on a user’s device.

[0049] The pathogen database **450** may store a plurality of deep learning algorithms **452**, **452a-n** and a plurality of

pathogen fingerprint profiles **454**, **454a-n**. The pathogen database **450** may be customizable with the deep learning algorithms **452**, **452a-n** to identify, increase, improve robustness of, and expand the pathogen fingerprint profiles **454**, **454a-n** to decrease operator error, resulting in the MAI-IMS device **100a** being an ideal portable device for universal pathogen onsite screening.

[0050] The pathogen detection application **430** used to classify microorganisms may be based on multivariate statistics including, but not limited to, e.g., principal component analysis (PCA) to generate PCA data, orthogonal projections to latent structures discriminant analysis (OPLS-DA) to generate OPLS-DA data, random forests (RF) to generate RF data, and/or library matching to generate library matching data. The PCA may be an unsupervised technique for visualizing variance in the observations. For example, classification may not be defined and may depend on spectral variance to the group. The pathogen detection application **430** using PCA may reduce the dimensionality of the complex spectral features allowing them to be visualized in a 2D or 3D plot.

[0051] OPLS-DA, as implemented by the pathogen detection application **430**, may be a supervised technique in which group classification may be manually set. As just two examples, the pathogen detection application **430**, utilizing OPLS-DA, may manually set the group classification for *Mycobacterium smegmatis* (M. smeg) MC<sup>2</sup> 155 and *Escherichia coli* (E. coli) K-12. The pathogen detection application **430** using OPLS-DA may identify which variables (molecular features) from the MAI-IMS fingerprints are causing the discrimination between the two classes.

[0052] RF, as implemented by the pathogen detection application **430**, may be a supervised technique used as an additional classification method. In some implementations, the pathogen detection application **430** may use loadings from the PCA data and raw MAI-IMS data collected from one of the bacteria as a training set to compare these data sets against the remaining observations to speed up the model.

[0053] Library matching, as implemented by the pathogen detection application **430**, may be done for each bacterial fingerprint separately. In some implementations, the pathogen detection application **430** may use a penalized non-negative linear regression framework using the limited samples for species-specific prototypes, which may be derived directly from the routine reference database of pure spectra.

[0054] In some implementations, the pathogen detection application **430** may train the plurality of deep learning algorithms **452**, **452a-n** using the following exemplary process based on at least one of the pathogen fingerprint profiles **454**, **454a-n**, the MAI-IMS data collected from the sample **106a**, the PCA data, the OPLS-DA data, the RF data, and the library matching data.

[0055] The pathogen detection application **430** may obtain the MAI-IMS data from the sample **106a** and pre-process the MAI-IMS data by noise removal, normalization, scaling, and data alignment. The pathogen detection application **430** may then perform PCA on the pre-processed MAI-IMS data to visualize the clustering of microorganisms. The pathogen detection application **430** may then train the OPLS-DA process and the RF process by splitting the pre-processed MAI-IMS data into training and test sets. The pathogen detection application **430** may then fit the models of the OPLS-DA process and the RF process to the training data.

During the training, the pathogen detection application 430 may select variables or features that cause classification. The pathogen detection application 430 may use the models to predict the identity of unknown microorganisms. The pathogen detection application 430 may evaluate the model's performance using accuracy, precision, recall, and F1-score. The pathogen detection application 430 may implement OPLS-DA and RF processes to prevent overfitting and assess stability.

[0056] The pathogen detection application 430 may implement the deep learning algorithms 452, 452a-n using convolutional neural networks (CNNs) to analyze the MAI-IMS generated datasets of microorganism/pathogen fingerprints. In some implementations, the pathogen detection application 430 may obtain the MAI-IMS data from the sample 106a and pre-process the MAI-IMS data by noise removal, baseline correction, peak alignment, scaling, and normalization to correct for instrument performance and sample preparation variations. The pathogen detection application 430 may use the MAI-IMS data to extract relevant features and use them as inputs for the CNNs. The pathogen detection application 430 may select the relevant features using PCA. The pathogen detection application 430 may use a 1D CNN and train the 1D CNN using the pre-processed MAI-IMS data using stochastic gradient descent to optimize the network parameters. The pathogen detection application 430 may validate the model's performance to assess accuracy, precision, and robustness by examining metrics such as recall and F1-score.

[0057] The MAI-IMS device 100a allows samples to be spontaneously ionized with an addition of a particular MAI matrix when exposed to the vacuum of the mass spectrometer 10 via a heated inlet tube of the sampling rod 116. A micro-droplet of a matrix (~0.2  $\mu$ L) may be exposed to the vacuum at the aperture of the spectrometer 10 inlet. The differential pressure created when introducing a sample into the inlet (1.0 atm to  $1.0 \times 10^{-3}$  atm) and heat (40° C. to 150° C.) may promote the matrix-assisted ionization process. However, in some implementations, a heat source may not be necessary.

[0058] In some implementations, the MAI-IMS device 100a may be used in extraterrestrial applications. For example, the MAI-IMS device 100a may be used to analyze terrestrial or nonterrestrial samples while in outer space, on satellites, on space stations, etc. In other implementations, the MAI-IMS device 100a may be used in military and defense applications, such as bioterrorism threats or other concerns. In other implementations, the MAI-IMS device 100a may be used in transportation applications, such as airports, train stations, shipping docks, etc. In other implementations, the MAI-IMS device 100a may be used in environmental applications, e.g., in remote areas where accessibility to pathogen detection devices may be limited.

[0059] While this specification contains many specifics, these should not be construed as limitations on the scope of the disclosure or of what may be claimed, but rather as descriptions of features specific to particular implementations of the disclosure. Certain features that are described in this specification in the context of separate implementations can also be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable sub-combination. Moreover, although features may

be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a sub-combination or variation of a sub-combination.

[0060] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multi-tasking and parallel processing may be advantageous. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products.

[0061] A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. Accordingly, other implementations are within the scope of the following claims. For example, the actions recited in the claims can be performed in a different order and still achieve desirable results.

What is claimed is:

1. A device for detecting pathogens comprising:
  - a chamber configured to receive a sample including an analyte and a matrix;
  - a gas inlet extending into the chamber and configured to adjust the pressure within the chamber to ionize the molecules of the sample;
  - an ion mobility spectrometer configured to obtain the ionized molecules of the sample to obtain pathogen data; and
  - a computing device configured to analyze the pathogen data to determine one or more pathogens of the analyte.
2. The device of claim 1, further comprising a housing configured to house the chamber, the ion mobility spectrometer, and the computing device.
3. The device of claim 2, wherein the housing is configured to be handheld.
4. The device of claim 1, further comprising a heat source within the chamber configured to adjust the temperature within the chamber.
5. The device of claim 1, wherein the computing device analyzes the pathogen data using artificial intelligence.
6. The device of claim 5, wherein the artificial intelligence includes deep learning algorithms to improve the robustness of the analysis of the pathogen data.
7. The device of claim 1, further comprising an airlock door configured to selectively permit access to the chamber.
8. The device of claim 1, further comprising a sampling rod configured to selectively transmit the sample into the chamber.
9. A system for detecting pathogens comprising:
  - a pathogen detection device comprising:
    - a chamber configured to receive a sample including an analyte and a matrix;
    - a gas inlet extending into the chamber and configured to adjust the pressure within the chamber to ionize the molecules of the sample;

- an ion mobility spectrometer configured to obtain the ionized molecules of the sample to obtain pathogen data; and
- an external computing device in communication with the pathogen detection, the external computing device configured to analyze the pathogen data to determine one or more pathogens of the analyte.
- 10.** The system of claim **9**, wherein the external computing device is one of a smartphone, a laptop computer, a desktop computer, or a tablet computer.
- 11.** The system of claim **9**, wherein the pathogen detection device is in communication with the external computing device via a wireless telecommunication network.
- 12.** The system of claim **9**, wherein the external computing device includes data processing hardware and memory hardware in communication with the data processing hardware, the memory hardware storing instructions that when executed on the data processing hardware cause the data processing hardware to perform operations to analyze the pathogen data to determine one or more pathogens of the analyte.
- 13.** The system of claim **12**, wherein the operations include analyzing the pathogen data using artificial intelligence.
- 14.** The system of claim **9**, wherein the external computing device is in communication with cloud computing resources storing a pathogen database including a plurality of deep learning algorithms and a plurality of pathogen fingerprint profiles.

- 15.** A method for detecting pathogens comprising:  
introducing a sample into a pathogen detection device;  
adjusting the pressure within the pathogen detection device to ionize the molecules of the sample;  
introducing the ionized molecules of the sample into an ion mobility spectrometer;  
operating the ionized mobility spectrometer;  
obtaining pathogen data from the ionized mobility spectrometer related to the ionized molecules of the sample;  
analyzing the pathogen data; and  
determining at least one pathogen of the sample based on the analysis of the pathogen data.
- 16.** The method of claim **15**, wherein the pathogen detection device and the ion mobility spectrometer are contained within the same housing.
- 17.** The method of claim **15**, wherein the pressure within the pathogen detection device is adjusted via a gas inlet into the pathogen detection device.
- 18.** The method of claim **15**, further comprising adjusting the temperature within the pathogen detection device via one of an ultraviolet lamp or an infrared lamp.
- 19.** The method of claim **15**, wherein the pathogen data is analyzed using artificial intelligence.
- 20.** The method of claim **19**, wherein the pathogen data is analyzed using one or more deep learning algorithms to improve the robustness of the analysis of the pathogen data.

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