September, 2024

Keywords or phrases:
AAV, Adenovirus, Antiviral Drug, Astrovirus, Bacteriophage, Chikungunya, Concentration, Coronavirus, Ebola, Enterovirus, Gene Therapy, Hepatitis, Herpesvirus, HIV, Lentivirus, MERS, Mpox, Norovirus, Pathogen Surveillance, Parvovirus, Poxvirus, Purification, Rotavirus, Sapovirus, SARS, Ultrafiltration, Vaccine, Vaccinia, Viral Vector, Virioplankton, Virus, Virus-Like Particle, Wastewater

Concentration and Purification of Viruses by Ultrafiltration – a Short Review

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Abstract

This short review summarizes concentration and purification steps for various viruses in the context of different research applications. The discussed methods have been employed in medical research, monitoring aquatic viruses in the marine environment, and analysis of drinking water and food quality. Furthermore, the persistent threat posed by pathogens with epidemic and pandemic potential has - especially in recent years - brought viruses such as ebola (e.g. EBOV), coronaviruses (e.g. MERS-CoV, SARS-CoV-1 and SARS-CoV-2) and poxviruses (e.g. MPXV) into the spotlight. In these cases, ultrafiltration has broad applicability, from general research, to novel vaccine and treatment development, and disease surveillance. We highlight numerous examples where Vivaspin® and Vivaflow® ultrafiltration devices have been used in each of these research areas, and include guidance towards selection of the optimal device and molecular weight cut-off (MWCO).

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Introduction

Throughout evolution, viruses have developed various mechanisms to interact with and manipulate the genetic material of their target cells. Based on this, modern molecular biology utilizes viruses in a constantly growing number of applications.[1] They range from controlled genetic transfection of cells to a variety of basic studies in medical science.[2] In medical studies the strategic focus is on recombinant vaccines and the development of potential vectors for gene therapy.[3,4]

Besides the great relevance of viruses for medical applications, the assessment of virus type and content is important for the risk assessment of food and drinking water.[5] Also, the classification of virus content is often of high relevance for the quality control of aquatic biotopes.[6]

During the preparation, handling, or analysis of viruses or virus-like particles (VLPs), a concentration and/or purification step is frequently required.[5] Typical viruses have a size within the range of about 20 nm up to several hundred nanometers.[7] Therefore they are ideally suited for retention by ultrafiltration membrane systems and such ultrafilters are widely used in virus research. Specification of the optimal ultrafiltration device typically depends on the particular type of virus, the purpose of ultrafiltration and the subsequent application.

This short review highlights methods for concentration and purification of viruses - especially those which cause illness or disease in humans and other mammals. We summarize the use of ultrafiltration for these processes in the context of medical research, analysis of water and food samples, the purification of marine bacteriophages (virioplankton), and research into new and emerging viruses to understand and monitor transmission, disease spread and novel vaccine development. We also provide guidance for the selection of an ideal performing device with the optimum molecular weight cut-off (MWCO) for each ultrafiltration process.

Applications

Concentration of Viruses in Medical Research

In medical research viruses and VLPs are of major interest, particularly for investigations on infectious viral diseases and for the development of vaccines or antiviral drugs. Moreover, certain VLPs can manipulate genetic material in a directed manner and are used broadly in the development of gene therapy approaches. Additionally, viral vectors are well established as a transfection method for gene transfer into cell lines, for example to manipulate mammalian cells *in vivo* and *in vitro.*

An overview of thematically linked publications using Sartorius ultrafiltration devices for the purification and concentration of viruses and VLPs in the medical context is given in Table 1. Among other applications, Vivaspin® devices were employed for the concentration of adeno-associated virus (AAV) and lentiviral vectors after purification via ion exchange chromatography[8–10], on blood sera to prepare neagtive controls from hepatitis C virus (HCV)-positive samples,[11] and for the development of a vaccine against human immunodeficiency virus (HIV) and of an antiviral drug against Chikungunya virus.[12,13] Furthermore, Vivaspin® devices have been used to prepare ebola virus (EBOV) glycoprotein nanoparticles prior to vaccine efficacy testing in mice[51] and vaccinia virus (VACV) epitope concentration in deimmunization studies towards novel cancer treatments[58].

Concentration of Viruses from Drinking Water and Food Samples

The guidelines for drinking water quality by the World Health Organization (WHO) describe safety plans to reduce potential risks of various viral infections.[16] They state that, due to the increased resistance of viruses to disinfection methods, an absence of bacterial contamination after disinfection cannot be used as a reliable indicator of the presence or absence of pathogenic viral species in drinking water supplies. Considering this, ultrafiltration can play a vital role towards detecting such viral contamination for research into drinking water quality and food safety.

Prior to ultrafiltration, there is no requirement for samples to be pre-conditioned and concentration efficiency is virtually independent of the chemical properties and structure of the virus.[17] Thus ultrafiltration is very well suited to isolate and concentrate virus particles from water samples and is a valuable aid during the assessment of water quality. Most of the viruses which are found in water and also food samples are of fecal origin. Screening for these viruses - the most frequent being hepatitis A, hepatitis E and norovirus - is therefore crucial to preventing infection outbreaks.[18] Ultrafiltration has been described as the most appropriate method for the recovery of hepatitis A virus from vegetables and other food items.[19] Detection of infectious viruses is mainly done by propagation in cell culture (plaque assay) or the detection of the viral genomes by molecular amplification techniques such as quantitative reverse transcriptase polymerase chain reaction (RT-PCR).[20]

Table 1

Examples of applications using Vivaspin® and Vivaflow® for virus concentration and purification in medical research.

Goal of Research (Type of virus, Host Organism)	**Purpose of Filtration (Buffer System)**	**Sartorius Ultrafiltration Device (MWCO)**	**Subsequent Step**	**Ref.**
Gene therapy (Adenovirus type 5, VLP, human)	Diafiltration (20 mM Tris saline buffer)	Vivaflow® (100 kDa)	Storage, chromatography on Sartobind STIC (FPLC)	14
Reduction of HCV-induced fibrosis (Hepatitis C Virus; human)	Removal of HCV from human blood serum (Blood serum)	Vivaspin® (30 kDa)	Immunofluorescence assay, fibrosis induction assays	11
Development of a viral entry inhibitor for HIV (HIV, human)	Removal of protein fraction from virus (PBS)	Vivaspin® 20 (1,000 kDa)	Virus inactivation	12
Gene therapy for cancer treatment (adeno-associated virus; rAAV-2, human)	Concentration and purification after expression, Buffer exchange after His tag (FreeStyle 293 Expression Medium (Gibco), serum-free)	Vivaspin® 20 (1,000 kDa)	Titer, ELISA, cell binding assay, apoptosis | cell cycle assay	8
System for controlled gene expression in mice brain (Adeno-associated virus, mice)	Concentration of eluate after anion exchange chromatography (elution buffer)	Vivaspin® 20 (100 kDa)	Transduction of mice neurons	9
Efficient gene transfer into the CNS (Lentivirus, human)	Concentration after ion exchange chromatography (PBS)	Vivaspin® (100 kDa)	Real-time PCR and end-point dilution. Transduction of murine neuronal and glial cells *in vivo*	10
Identification of effective chikungunya antiviral drugs (Chikungunya-Virus, human)	Concentration	Vivaspin® 20 (100 kDa)	Quantification by $TCID_{50}$	13
Gene therapy of achromatopsia in mice (Recombinant adeno-associated virus, human virus used in mice)	Concentration (Anion exchange chromatography elution buffer)	Vivaspin® 4 (10 kDa)	Titer determination by dot-blot analysis, subretinal injections	15
Vaccine efficacy testing (EBOV glycoprotein nanoparticles, mouse)	Concentration	Vivaspin® 500 (30 kDa)	Dilution with excipient, coating microneedle patches, BCA assay, SDS PAGE, western blot, quantitative ELISA, vaccination	51
Deimmunization of VACV (recombinant p35 epitopes from VACV, mouse)	Concentration (50 mM Tris-HCl, 150 mM NaCl, pH 7.5)	Vivaspin® Turbo 15 (10 kDa PES)	Immunization	58

Table 2:

Examples of ultrafiltration using Vivaspin® and Vivaflow® for virus concentration from drinking water and food samples.

Goal of Research (Type of virus, Host Organism)	**Purpose of Filtration (Buffer System)**	**Sartorius Ultrafiltration Device (MWCO)**	**Subsequent Step**	**Ref.**
Method for the detection of norovirus genogroup I (Norovirus, human)	Concentration (PBS processed food samples)	Vivaspin® (5 kDa)	RNA extraction for real-time RT-PCR	22
Analysis of viral content in groundwater (A set of pathogenic viruses, potentially human)	Concentration of drinking water sample (Drinking water)	Vivaflow® 200 (10 kDa)	RT-nested PCR and microtiter neutralization test	21
Comparative Analysis of Viral Concentration Methods (Hepatitis A virus, human)	Concentration (0.25 M threonine, 0.3 M NaCl, pH 9.5)	Vivaspin® 20 (100 kDa)	RNA extraction for real-time RT-PCR	19
Analyzing regional gastroenteritis outbreak due to drinking water contamination (Norovirus, Astrovirus, Rotavirus, Enterovirus, Hepatitis A; human)	Concentration (50 mmol/L glycine buffer, 1% beef extract)	Vivaspin® 2	Nucleic acid extraction	23

Concentration of Viruses and Bacteriophages from Marine Samples

In marine biology, the concentration and subsequent analysis of marine bacteriophages (virioplankton) is of major interest. They outnumber the bacterioplankton (their host organisms) by an order of magnitude and thus have an important influence on the whole marine biosphere.[24]

As described by Wyn-Jones & Sellwood (ref. 17) ultrafiltration can be used to concentrate virus particles in water samples without any prior pretreatment of the sample and it is also practically independent from the chemical and structural properties of the viruses. Thus, it finds wide use for the analysis of aquatic viruses. For instance, Schroeder *et al.* (ref. 26) were able to determine the diversity and monitor population dynamics of viruses that infect *Emiliania huxleyi*, a globally important photosynthetic plankton. In this study a reusable Vivaflow® 50 unit equipped with a 50 kDa MWCO polyethersulfone (PES) membrane was used to concentrate viruses in sea water samples prior to storage and analysis. For further examples of virus concentration from marine biological samples, see table 3.

Table 3

Examples of ultrafiltration applications using Vivaflow® and Vivaspin® for samples from the marine environment.

Goal of Research (Type of virus, Host Organism)	Purpose of Filtration (Buffer System)	Sartorius Ultrafiltration Device (MWCO)	Subsequent Step	Ref.
Assessment of virioplankton diversity (Virioplankton, Plankton)	0.2 µm filtration for clarification, filtrate subjected to 3 kDa filter for concentration (Sea water)	Vivaflow® 200 (0.2 µm and 30 kDa)	Subsequent analysis by DNA separation on Agarose gel	25
Classification of virus (MpRNAV-01B, *Micromonas pusilla*)	Vivaflow 200: harvest and concentration of whole cell lysate; Vivaspin: washing (removal of CsCl)	Vivaflow® 200, Vivaspin® (30 kDa)	Classification of new virus: genome, proteins, stability, etc.	28
Assessment of genetic diversity in virioplankton (*Emiliania huxleyi* Bloom virus, Eukaryotic phytoplankton - alga)	After 0.45 µm filtration, concentration 1l to 20 ml (Sea water)	Vivaflow® 50 (50 kDa)	PCR and Denaturing gradient gel electrophoresis	26
Investigation of gene expression during infection (*Emiliania huxleyi* virus strain 86, Eukaryotic phytoplankton - alga)	Concentration from 5 L to 20 ml (f/2 medium)	Vivaflow® 50 (50 kDa)	CsCl-gradient	27
Study on host genome integration (*virophage mavirus, Cafeteria roenbergensis*)	Clarification with 0.2 µm filter and concentration with 100 kDa filter (*Cafeteria roenbergensis*, f/2 medium)	Vivaflow® 200 (0.2 µm and 100 kDa)	CsCl gradients, electron microscopy	29

Concentration of Coronavirus and its Proteins for General Research

Coronaviruses are spherical, enveloped, RNA based viruses that are typically 80-120 nm in diameter, but in many cases have a diameter outside of this range. Coronavirus genomes are the largest of all RNA viruses which offers a relatively large area of study. Together with high rates of infection, the high chance for future mutations in their large genomes may lead to future human diseases with potential to develop into epidemics and pandemics, such as the recent Middle East Respiratory Syndrome (MERS-CoV), and Severe Acute Respiratory Syndrome 1 (SARS-CoV-1) and 2 (SARS-CoV-2) outbreaks. Hence, further research into the replication, transmission, genome and structure will continue with greater investment of time and funding in the years to come.

A key component to the infection cycle is the coronavirus spike (S) protein, that mediates entry into host cells, through both attachment and membrane fusion. As such, it is a primary target for the development of novel antiviral drugs and vaccines.

The concentration and purification of both the virons and the spike proteins from cell culture supernatants is often a key requirement to isolate the respective target, prior to structural and functional analysis.

Table 4 highlights several applications where Vivaspin® centrifugal concentrators, or Vivaflow® tangential flow filtration cassettes have been used for the concentration of coronavirus proteins, including the spike protein.

Table 5 provides examples where intact virons or VLPs have been concentrated using the same devices, for various coronaviruses, as well as for a model ebola virus.

Table 4

Examples of concentration and diafiltration of coronavirus proteins using Vivaflow® and Vivaspin®.

Goal of Research (Type of virus, Host Organism)	Purpose of Filtration (Buffer System)	Sartorius Ultrafiltration Device (MWCO)	Subsequent Step	Ref.
Neutralization of a SARS-CoV-2 antibody to a functionally conserved receptor binding domain (RBD) on the trimeric spike (S) protein	Buffer exchange of a SARS-CoV-2 RBD protein	Vivaspin® 20 (10 kDa PES)	Protein concentration by UV/Vis and binding affinity by Streptavidin BLI (Sartorius Octet)	30
Investigation of neutralising antibody response on a SARS-CoV-2 spike glycoprotein RBD-SpyVLP (virus-like particle) platform	Concentration of SpyTag-RBD protein construct	Vivaspin® 20 (10 kDa PES)	Purification by SEC	31
Investigation of exosome based vaccines containing coronavirus spike (S) protein, for SARS-CoV-1	Concentration of solubilized spike protein in supernatant	Vivaspin® (10 kDa PES)	Western blot analysis	32
Analyze of the ability to redirect the functionality of the Mouse Hepatitis Coronavirus spike (S) protein to infect human cancer cells	Concentration of cellular receptor protein constructs	Vivaspin®, PES	Western blot analysis	33
Structure determination of Coronavirus SARS-CoV-1 non-structural protein 1 (nsp1)	Concentration of coronavirus nsp1 during purification process	Vivaspin®, PES	Crystalization screening	34
Structure determination of the ADRP domain of Feline Coronavirus (FCoV) non-structural protein 3 (nsp3)	concentration of coronavirus nsp3 during purification process	Vivaspin® (10 kDa PES)	Crystalization screening	35
Investigation into the role of three transmembrane proteases in the activation of SARS-CoV-1 spike (S) protein	Concentration of VLPSs from HEK 293T cell culture supernatant	Vivaspin®, PES	Cell-cell fusion assay	36
Cryo-electron microscopy of Human Coronavirus HCoV-NL63 spike glycoprotein trimer that is a potetial target for neutralizing antibodies during infection	Concentration of recombinant HCoV-NL63 viruses from clarified Drosophila S2 cell culture supernatant	Vivaflow® (10 kDa PES)	Affinity purification	37

Table 5

Examples of applications using Vivaspin® for coronavirus and ebola viron and VLP sample concentration.

Goal of Research (Type of virus, Host Organism)	Purpose of Filtration (Buffer System)	Sartorius Ultrafiltration Device (MWCO)	Subsequent Step	Ref.
Characterisation of phenotypic changes in virus isolates, such as MERS-CoV, that could relate to pandemic potential	Concentration of MERS-CoV virus isolates	Vivaspin® (100 kDa PES)	Quantification using plaque titration Viral RNA sequencing analysis	38
Investigation of antiviral potential of Echinacea purpurea (Echinaforce®) against human coronaviruses; SARS-CoV and MERS-CoV	Concentration of MERS-CoV and SARS-CoV virus dilutions	Vivaspin® 20, PES	Limiting dilution assay ($TCID_{50}$)	39
Investigation into inactivation of SARS-CoV-2 through heating and chemical protocols	Concentration and separation of deactivated SARS-CoV-2 from lysis buffer	Vivaspin® 500, PES	Inoculation onto Vero-E6 monolayer	40
Investigation of viral and cellular determinants governing hCoV-EMC entry into host cells	Concentration of SARS-CoV and hCoV-EMC virus like particles (VLPs)	Vivaspin®, PES	Western blot analysis	41, 42
Understanding host cell entry and egress pathways (Ebola model virus: rVSV/EBOV-GP, Vero cells)	Concentration and purification (Iscove's medium)	Vivaspin® 20 (300 kDa PES)	qRT-PCR, plaque assay	52

Concentration of Virions and | or Viral Genomic Material from Wastewater

In humans and birds, coronaviruses may inflict mild to fatal respiratory tract infections, but in other animal groups a range of other diseases may also occur, such as hepatitis and neurological illness[42]. SARS-CoV-2 is the most recent among a string of coronavirus epidemics, which, due to its high infectivity, rates of asymptomatic infection, significant incubation time, our relatively limited knowledge of transmission dynamics and overall lack of global pandemic preparation, developed into a true global pandemic, causing significant impacts on global health, society and economy.

The severity of this pandemic is driving increased research and funding in all associated areas. One area is on the tracking and epidemiological studies of SARS-CoV-2 infections, with a particular focus on the use of regional wastewater systems, where the compartmentalisation of these systems offers distinct tracking in real time, without the lag for symptom appearance and clinical diagnosis[43]. In addition, the data collected can be used as a supplemental and low-cost surveillance indicator on the circulation of the virus in a community without the need to screen individuals. Further, it contributes to the tracking of infection prevalence, by adding another epidemic indicator[44].

RT-PCR is the standard method to test for SARS-CoV-2, but samples typically require concentration and removal of non-coronavirus material prior to testing to ensure optimal results. Ultrafiltration is a successful method for this[43], and some examples have been given in Table 6.

Table 6

Examples of ultrafiltration with Vivaflow® and Vivaspin® for virus and viral RNA concentration from wastewater samples.

Goal of Research (Type of virus, Host Organism)	Purpose of Filtration (Buffer System)	Sartorius Ultrafiltration Device (MWCO)	Subsequent Step	Ref.
Measurement of SARS-CoV-2 RNA in sewage	Concentration of viral RNA	Vivaspin® (50 kDa PES)	Viral RNA extraction and purification RT-qPCR quantification	43, 44
Benchmarking virus concentration methods for quantification of SARS-CoV-2 in raw wastewater	Concentration of viral RNA	Vivaspin® 100 (10 kDa PES)	Viral RNA extraction and purification RT-qPCR quantification	45
Evaluation of two methods to concentrate SARS-CoV-2 from untreated wastewater	Concentration of viral RNA from 40 ml (total) to 700-1000 µl	Vivaspin® (10 kDa)	Viral RNA extraction and RT-qPCR and ddPCR quantification	46
Virus detection in full scale membrane bioreactor (MBR) plant by virus concentration monitoring, inc. Norovirus, Sapovirus and Rotavirus	Concentration of viral particles in effluent	Vivaflow® 50, PES	PEG precipitation Viral RNA quantification	47
Evaluation of membrane bioreactor wastewater virus removal, inc. Norovirus, Sapovirus, Adenovirus	Concentration of effluent from 1L to 40mL	Vivaflow® 50, PES	Nucleic acid extraction RT-PCR quantification	48
Evaluation of membrane bioreactor wastewater Norovirus removal	Concentration of viruses in effluent	Vivaflow® 50, PES	Nucleic acid extraction RT-PCR quantification	49
Evaluation of the association between number of hepatitis E cases in the community and concentration in local sewage	Concentration of viruses in effluent	Vivaflow® 50, PES	Nucleic acid extraction RT-qPCR quantification	50

Concentration of Poxviruses for General Research and Environmental, Animal and Wastewater Sample Analysis

The global effort which culminated in eradication of the variola virus in 1979 was a major achievement in recent history.[53] However, its potential use as a biological weapon and the 2022 outbreak and emergence of a new strain in 2023 of the closely related mpox (previously known as monkeypox) demonstrate that the poxviruses can still pose a substantial threat to human health.

The 2022 and 2024 mpox outbreaks were designated by the WHO as global health emergencies, due to the spread to non-endemic countries, the emergence of a new clade of the virus, and potential changes to how the virus is transmitted.[54-56] Further challenges to controlling such outbreaks might also be presented by the long-term stability of orthopoxviruses, and their potential for evolution through recombination, as well as development of resistance against antiviral drugs.[55-56] Therefore, it is important to develop a deeper understanding of mpox and similar viruses to support the development of novel control measures, vaccines and treatments.

As for other viruses, ultrafiltration can be used to concentrate and purify poxviruses, and we would suggest higher MWCOs of around 100 - 1,000 kDa, due to their relatively large dimensions of 220 - 450 by 140 - 260 nm, respectively.[59] Examples where Vivaflow® and Vivaspin® have been used in general research, and the analysis of poxvirus content in environmental and animal samples are presented in Table 7.

Finally, to draw parallels with Poliovirus and SARS-CoV-2, MPXV, the virus that causes mpox, is similarly shed in the faeces of infected individuals prior to symptom onset.[60] This makes wastewater surveillance an attractive technique for monitoring the prevalence and spread of monkeypox infections, as well as the potential emergence of new MPXV variants as the outbreak progresses. Such surveillance methods are already being adapted for and extended to include MPXV in the USA and Thailand.[60-62] For this purpose, based on the size and shape of MPXV particles (200-250 nm and brick- or egg-shaped) and genome length (190 kbp)[54], a 100 or 300 kDa MWCO ultrafiltration membrane might be best suited for optimal particle and DNA recovery, while permitting the removal of low molecular weight interfering substances, during the wastewater sample concentration step.

Table 7

Examples of ultrafiltration with Vivaflow® and Vivaspin® for concentration of poxviruses and their proteins.

Goal of Research (Type of virus, Host Organism)	Purpose of Filtration (Buffer System)	Sartorius Ultrafiltration Device (MWCO)	Subsequent Step	Ref.
Isolation of macromolecular complexes from poxvirus infected cells	Concentration	Vivaspin ® 500 (10 kDa)	Sucrose density gradient ultracentrifugation, denaturing PAGE	63
Structure determination (Vaccinia virus RNA polymerase)	Concentration and sucrose removal	Vivaspin®	cryo-EM	64
Ectromelia virus (ECTV) E163 protein interaction with cell surface glycosaminoglycans (GAGs)	Concentration	Vivaspin® 500 (10 kDa)	Flow cytometry	65
Virome characterization of Lake Baikal (*Myoviridae, Siphoviridae, Podoviridae, Phycodnaviridae* and *Poxviridae*)	Concentration	Vivaflow® 200 and Vivaspin® Turbo 15 (50 kDa)	PCR, Sequencing	66
Identification of virus content in pig faeces for aetiology, epidemiology and disease ecology (various mammalian viruses, including Rotavirus, Enterovirus, Sapovirus, Parvovirus, Herpesvirus and Poxvirus)	Concentration	Vivaspin® (50 kDa)	CsCl density gradient ultracentrifugation, deep sequencing	67

Conclusion

The concentration and purification of viruses by ultrafiltration is virtually independent of the chemical properties and the structure of the virus particles. As viruses have a size ranging from tens up to several hundred nanometers, they are typically several orders of magnitude bigger than even the largest protein complexes.[7] Therefore, most viruses are unfailingly retained on membranes with MWCOs up to 1,000 kDa. The exact specifications of the ideal ultrafiltration membranes depend on the purpose of ultrafiltration and the subsequent application(s).

During the preparation of viral vectors for medical studies, a buffer exchange after column purification can be performed with various MWCOs of all sizes.[8,9,10,15] To separate virus particles from small proteins, a 1,000 kDa cut off has been shown to be effective.[12] For the complete removal of HCV from blood serum a 30 kDa MWCO has been utilized.[11] When the assessment of whole virus content is crucial (e.g. food, drinking water or environmental samples) smaller MWCOs (5 – 100 kDa) are used to ensure full recovery of virus particles.[19,21,22,25-29,66-67]

Ultrafiltration for the concentration of coronavirus species plays an important role in a range of workflows. Perhaps due to the size distribution of viruses and VLPs, there is no standard MWCO used in each study. Typically, for 80-120 nm particles, a 100 kDa MWCO would provide the optimal balance between recovery, removal of interfering substances, speed and shear stresses. However, for the recovery of RNA material, lower MWCOs (10-50 kDa) are recommended to capture a broader range of RNA fragment lengths.

It is a similar situation - albeit with fewer examples in the published literature so far - for the concentration of other infectious viruses. For example, ebola and poxviruses have been concentrated using MWCOs of 300 kDa and 50 kDa , respectively. [51,66-67] Therefore, until standards are set for each application, it is prudent to test multiple devices and MWCOs when developing an ultrafiltration-based concentration or purification process, especially for new viruses for interest.

Note

Vivaspin® 100 is part of the Vivaspin® product family. Literature published up to c.2022 may reference the use of Vivacell 100, which is a name previously used for the same centrifugal | pressure-driven ultrafilters. When these devices were renamed, there was no change made to fit, form or function, so results collected using Vivacell 100 devices remain valid also for Vivaspin® 100.

Abbreviations

AAV	Adeno-associated virus
CNS	Central nervous system DNA Deoxyribonucleic acid
CoV	Coronavirus
EBOV	Ebola virus
ELISA	Enzyme-linked immunosorbent assay
FPLC	Fast protein liquid chromatography
fCoV	Feline Coronavirus
hCoV	Human Coronavirus
HCV	Hepatitis C virus
HIV	Human immunodeficiency virus
kDa	Kilodalton (1,000 g per mole)
M	Molarity (mole per litre)
MERS	Middle east respiratory syndrome
mol	Mole
MPXV	Monkeypox virus
MWCO	Molecular weight cut-off
nsp	Nonstructural protein
PAGE	Polyacrylamide gel electrophoresis
PBS	Phosphate buffered saline
PCR	Polymerase chain reaction
PEG	Polyethylene Glycol
PES	Polyethersulfone
RNA	Ribonucleic acid
SARS	Severe acute respiratory syndrome
RBD	Receptor binding domain
BLI	Bio-Layer Interferometry
RT-PCR	Reverse transcriptase-polymerase chain reaction
ddPCR	Droplet digital polymerase chain reaction
TCIDP50	50% Tissue culture infective dose
VLP	Virus-like particle

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Version: 09 | 2024