

# Extracellular vesicles derived from Hepatitis-D Virus infected cells induce a proinflammatory cytokine response in human peripheral blood mononuclear cells and macrophages

## ✉ Correspondence

stephanie.jung@tum.de  
protzer@tum.de

## 📍 Disciplines

Virology  
Immunology

## 🔍 Keywords

Hepatitis D Virus  
Innate Immunity  
Extracellular Vesicles

## 🏠 Type of Observation

Standalone

## 🔗 Type of Link

Standard Data

🕒 Submitted Sep 22, 2019

📅 Published Feb 14, 2020



## 🔒 Triple Blind Peer Review

The handling editor, the reviewers, and the authors are all blinded during the review process.



## 🔓 Full Open Access

Supported by the Velux Foundation, the University of Zurich, and the EPFL School of Life Sciences.



## 📄 Creative Commons 4.0

This observation is distributed under the terms of the Creative Commons Attribution 4.0 International License.

**Stephanie Jung, Sebastian M Altstetter, Florian Wilsch, Mikhail Shein, Anne K Schütz, Ulrike Protzer**

Helmholtz Zentrum München / Technical University of Munich, School of Medicine, Institute of Virology; Technical University of Munich, Department of Chemistry; Helmholtz Zentrum München / Technical University of Munich, School of Medicine, Institute of Virology, German Center for Infection Research (DZIF), Munich partner site

## Abstract

Hepatitis D Virus (HDV) is a satellite virus requiring a Hepatitis B Virus (HBV) envelope proteins for productive infection. Hepatitis D is the most severe form of viral hepatitis and is a global health threat affecting 15 to 20 million humans. In contrast to the Hepatitis B Virus mono-infection, against which only a minor innate immune response is mounted at most, HBV-HDV coinfection is characterized by strong activation of innate immune responses. To shed light on poorly understood mechanisms of HDV-triggered disease progression, we focussed on the question how immune cells may be activated by HDV. We hypothesized that extracellular vesicles (EVs) released from infected cells mediate this activation. We, therefore, purified EVs from the supernatant of HDV-infected and non-infected cells and incubated them with human peripheral blood mononuclear cells (PBMC) and macrophages. Here we show for the first time that HDV infection leads to the production of EVs which subsequently mediate a proinflammatory cytokine response in primary human immune cells. These data might help to understand how HDV can be sensed by non-infected immune cells.

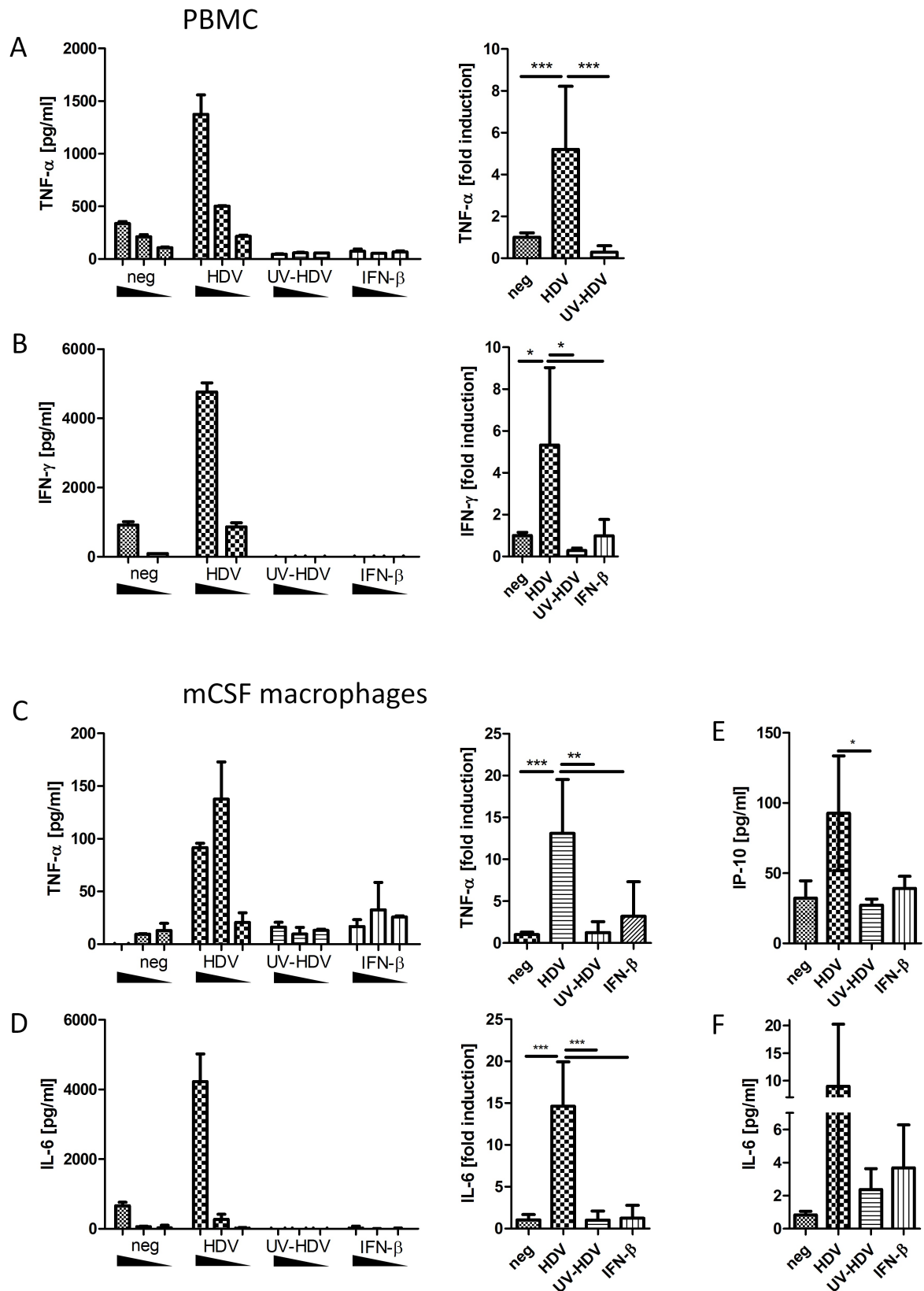
## Introduction

Extracellular vesicles (EVs) are small membranous particles selectively transferring cargo such as nucleic acids and cytokines between cells of origin and recipient cells as an essential mechanism of intercellular communication. They are classified by their mode of biogenesis as e.g. exosomes (40–100 nm), which are released from multivesicular bodies, or microvesicles (50 nm–1 µm) which directly bud from the plasma membrane. EV cargo delivery has been shown to mediate immunoregulatory effects via miRNAs, mRNAs, proteins and signaling molecules [1]. Regarding viral infections, EVs have been reported to exert both pro- and antiviral properties and to be responsible for transcellular spread, apoptosis, cytokine modulation and transfer of viral nucleic acids [2] [3] [4].

HDV is a satellite virus coexisting with HBV because it requires HBV envelope proteins for productive virion release and propagation of the infection [5]. In contrast to HBV mono-infection, which does not mount an interferon (IFN) response, HBV-HDV coinfection leads to a pronounced activation of the innate immune system [6] [7] and induces a robust proinflammatory cytokine release [8] [9]. In the clinics, this results in severe inflammatory liver disease with rapid progression to liver cirrhosis and hepatocellular carcinoma with high mortality. So far there is no directed therapy available, and there is an urgent need to better understand the interaction between HDV and host organism [10]. The cytoplasmatic RNA sensor MDA5 has recently been identified as the major pattern recognition receptor detecting HDV and inducing an interferon (IFN) response [11] [12]. But due to the lack of appropriate animal models, it remains elusive which immune cells contribute to HDV-dependent immune recognition, how these immune cells recognize HDV and how they contribute to disease pathogenesis.

## Objective

This study aimed at elucidating the mode of HDV-induced innate immune activation of primary human immune cells. In particular, we asked whether EVs derived from HDV-infected cells induce a proinflammatory cytokine response in primary human immune cells to slow down and whether this depends on HDV replication. Understanding the mode of immune cell activation by HDV may help to select therapeutic interventions to prevent or at least slowdown disease progression, and to combat this deadly disease.



a

**Figure Legend**

**Figure 1. Impact of Hepatitis D-Virus(HDV)-primed extracellular vesicles (EV) on primary human immune cells.**

(A-D) Human peripheral blood mononuclear cells (PBMC) (A, B) or macrophage-colony stimulating factor differentiated macrophages (mCSF macrophages) (C, D) were stimulated with EVs purified from the cell culture medium by Size-exclusion chromatography (SEC). Cell culture medium was collected either from untreated hepatoma cells (neg), HDV-infected cells (HDV), cells infected with UV-inactivated HDV (UV-HDV) or interferon b (IFN-b). The inoculum was normalized to the number of secreting cells and added in 5-fold dilutions. Supernatants collected from PBMC and mCSF macrophages were analyzed by ELISA. The left panel shows dose-dependent results from individual experiments with NTCP-expressing HepG2 (A, B, D) or Huh7 (C) derived EVs. The right panel depicts relative induction of cytokines by EVs released from treated versus non-stimulated hepatoma cells (neg). EVs were released by NTCP-expressing HepG2-cells only (A, B) or NTCP expressing HepG2 and NTCP-expressing Huh7 cells (C, D). Mean  $\pm$ SD from three (B, C, D) or six (A) independent experiments is given. Data were analyzed for normality using the D'Agostino-Pearson test, statistical analysis of the normally distributed data was done using paired t-tests. \*p <0.05, \*\*p <0.01, \*\*\*p <0.001.

(A) Tumor-necrosis factor- $\alpha$  (TNF- $\alpha$ ) released by PBMC. (B) Interferon- $\gamma$  (IFN- $\gamma$ ) released by PBMC. (C) TNF- $\alpha$  released by mCSF macrophages. (D) Interleukin-6 (IL-6) released by mCSF macrophages.

(E, F) mCSF macrophages were stimulated with EVs purified from the cell culture medium of primary human hepatocytes (PHH) which were untreated (neg), HDV-infected (HDV), infected with UV-inactivated HDV (UV-HDV) or treated with interferon b (IFN-b). The inoculum was normalized to the number of secreting cells. Supernatants were analyzed by ELISA and results are depicted as mean  $\pm$ SD from two independent experiments. Statistical analysis was performed using the Mann Whitney test. \*p <0.05.

(E) Interferon gamma-induced protein 10 (IP-10) released by mCSF macrophages. (F) IL-6 released by mCSF macrophages.

## Results & Discussion

To determine whether EVs released by HDV-infected cells (HDV-EVs) regulate innate immunity, we collected conditioned media of HDV-infected, non-infected or IFN- $\beta$  treated hepatoma cell lines [13]. Supernatants before purification and purified EVs (Suppl. Data 2A-C) were subjected to ELISA. No or only minimal amounts of proinflammatory cytokines were released from hepatoma cells in response to HDV infection, and EV preparation also contained only minute amounts of TNF- $\alpha$  (Suppl. Data 1).

Investigating the immune stimulatory role of EVs on primary human immune cells, HDV-induced EVs were incubated with human PBMC. This triggered TNF- $\alpha$  and IFN- $\gamma$  production by the PBMC in a dose-dependent manner (Fig. 1A and 1B). Cytokine release in response to EVs from non-infected cells or EVs produced in the presence of IFN- $\beta$  was significantly lower. Importantly, EVs derived from cells infected with UV-inactivated HDV did not induce TNF- $\alpha$  or IFN- $\gamma$  production indicating that intermediates from HDV replication were responsible cargo. Indeed, HDV mRNA could be detected in EVs released by HDV infected cells but not in EVs released by cells infected with UV-inactivated HDV (Suppl. Data 2D).

To find out which cell type is activated by HDV infection, we studied the effect on primary human macrophages because macrophages are the most frequently represented immune cells in the liver with up to 40 macrophages accompanying 100 hepatocytes [14]. Thus, macrophages were differentiated from monocytes using macrophage colony-stimulating factor mCSF and incubated with EVs. These macrophages released TNF- $\alpha$  and IL-6 in a dose-dependent manner after incubation with EVs obtained from HDV-infected cells, but not when HDV was treated with UV before infection, or when cells were only treated with IFN- $\beta$  (Fig. 1C, 1D and Suppl. Data 3). Consequently, viral transcription or HDV replication were essential to induce the release of immune stimulatory

EVs. Neither incoming HDV RNA nor the proteins contained in virions or IFN- $\beta$  that is released upon HDV infection were sufficient to trigger the release of EVs from infected cells that were immune-stimulatory.

To confirm results generated with EVs obtained from hepatoma-derived cells, primary human hepatocytes (PHH) were infected with HDV, UV-inactivated HDV or treated with IFN- $\beta$ . EVs were purified and used to stimulate mCSF Mf. (Fig. 1E, 1F). Although the signal was weak due to low numbers of EV secreting cells, mCSF Mf showed a trend to release interferon gamma-induced protein 10 (IP-10) and IL-6 in response to EVs from HDV-infected cells only.

Verifying availability of immunostimulatory entities in the blood of HDV-infected patients, EVs were purified from sera of HDV-positive (pos) or cured patients (neg 6y and neg 6m) and used to stimulate mCSF Mf (Suppl. Data 4). Both IL-6 and TNF- $\alpha$  were induced by EVs from HDV-positive samples only. However, EV samples purified from patient sera most likely still contain HBV and HDV virions not removed by SEC, which could also be immune-activating.

Taken together, these results demonstrate, that after productive HDV infection, i.e. HDV gene expression or replication, EVs are produced that activate a proinflammatory cytokine release from primary human immune cells. Most likely these EVs contain HDV RNA or replication intermediates as cargo and activate a pattern recognition response in the immune cells.

So far, it has not been clarified whether and to which extent HDV-induced innate immune activation occurs in infected hepatocyte or non-infected immune cells and which cells secrete the proinflammatory cytokine that contributes to disease progression [10]. PBMC comprise a mixture of various cell types. One main component of PBMC is monocytes, which were reported to be recruited to the inflamed liver where they differentiate to macrophages [15]. The liver itself, as a part of the mononuclear phagocyte system, is the organ harboring the highest percentage of macrophages in the body and has been shown to accumulate the largest proportion of EVs injected into the bloodstream [16] [14]. Consequently, we stimulated primary human macrophages with EVs purified from differentially conditioned media. In line with our results obtained in PBMC stimulation experiments, HDV-EVs specifically lead to proinflammatory cytokine release from mCSF-differentiated macrophages. This proves that macrophages respond to EV cargo affected by HDV infection but does not rule out that other cell types may be involved in a proinflammatory response in the liver upon HDV infection.

In our experiments, the conditioned media of HDV-infected hepatoma cell lines did only contain a minute amount of TNF- $\alpha$  and no other proinflammatory cytokines. The release was not evoked by HDV infection, as cytokine levels were higher in the media of non-infected than in the media of infected cells. It has been reported previously that transfection of large Hepatitis Delta antigen can enhance hepatocellular NF $\kappa$ B signaling in response to co-stimuli like TNF- $\alpha$  or plasmid DNA [8] [9]. By inactivating HDV with UV-light treatment prior to infection, however, we observed a complete loss of the immune stimulatory potential of EVs. Also mimicking pattern recognition of HDV infection by IFN- $\beta$  treatment and subsequent immune activation did not activate a proinflammatory response. Consequently, incoming viral genomes and proteins are not sufficient to trigger the release of immune-stimulatory EVs. Although we cannot completely rule out an effect of the higher amount of Hepatitis Delta antigen produced in infected cells, most likely viral replication intermediates, HDV mRNA or genomes are required.

It is very likely that response to HDV infection is provoked by EV mediated transfer of HDV-derived cargo. We could show that cytokine production from PBMC and macrophages in response to HDV-EVs was dose-dependent and most likely not due to EV associated cytokines. In line with our results, other studies report that EVs derived from various cell types can mediate pro-inflammatory effects in target cells [17] and that EVs induce cytokine secretion in response to HIV or HCV infection [18] [19]. The EV-mediated transfer was even shown to play a special role in infection with non-enveloped

viruses. While naked Hepatitis A Virus (HAV) failed to trigger plasmacytoid dendritic cell (pDC) activation, uptake of pseudo-enveloped HAV particles induced IFN- $\alpha$  production from human pDCs [20]. Hereby, RNA cargo was suspected to be responsible for immune activation. For HCV, type I IFN secretion of pDCs in response to stimulation with EV preparations containing HCV RNA has been reported [18]. In HIV infection, a pro-inflammatory cytokine response was shown to be mediated by exosomal Trans-activating Response (TAR) RNA [19].

Interestingly, during the course of infection with HDV's "host-virus", HBV, EVs released by HBV monoinfected cells seemed to have an immune-inhibitory function affecting monocytes, differentiated monocytic THP-1 and natural killer (NK) cells as well as IFN- $\gamma$  production and RIG I expression [21] [22] [23]. Consequently, innate immune activation by EVs is not a general mechanism linked to viral infections but specifically linked to HDV-induced EVs, and may even be hampered by HBV-coinfection *in vivo*. Upon others, this may be one reason why evolution selected HBV as a donor for the HDV envelope.

## Conclusions

We could show that EVs released from HDV-infected hepatoma cell lines and primary human hepatocytes induces a dose-dependent pro-inflammatory cytokine response in primary human immune cells like mCSF-differentiated macrophages and PBMC. As this effect was blocked by the previous inactivation of HDV, functional viral genomes seem to be crucial for innate immune activation. Further studies shall clarify which component is responsible for this effect. Understanding the mode of virus-mediated danger signal transmission will allow treating severe immunopathology and tissue damage in HBV-HDV coinfection.

## Limitations

The exact immune-stimulatory content of HDV-EVs remains to be identified, as this was limited by the low amount of EVs released from our cell lines. An exclusion of potential cytokine-mediated effects is also hindered by the fact that inactivation of cytokines by protease digestion or denaturation would also affect EV-associated proteins and thus the uptake of EVs that depends on their surface proteins [24]. Although our experiments demonstrate that macrophages respond to HDV-EVs, we cannot currently rule out that other cells also contribute to the response observed in PBMC. This study does not address the impact of HDV-EVs under natural conditions like HBV-HDV coinfection or *in vivo* models, as only HDV-mono-infection of hepatoma cell lines and primary human hepatocytes was used. EVs purified from patient sera are most likely contaminated with HBV and HDV virions, so observed proinflammatory cytokine induction only supports *in vitro* results. The development of reliable methods to remove virions from EV samples is urgently needed. Additionally, usage of plasma instead of sera for EV purification would be desirable but was not possible due to the lack of untreated HDV patients and conditions in blood banks.

## Alternative Explanations

Most recently, cytokine and growth factors have been reported as EV cargo [25]. TGF- $\beta$ , for example, seems to be more stable in a membrane-bound form than in a soluble form, indicating an important role of EVs as TGF- $\beta$  transporting vehicles [26]. Thus, the effect of cytokines not included in our assays cannot be ruled out. In addition, the transfer of second messengers via EVs is also conceivable, as a transfer of cGAMP by HIV virions has already been reported [27].

## Conjectures

Based on our data we hypothesize that RNA intermediates generated during HDV replication in infected cells become cargo of EVs released and can stimulate immune cells

inside and outside of the liver. Further investigations will have to follow proving this hypothesis and defining the immune stimulatory EV cargo in HDV infection.

## Additional Information

### Methods

#### Antibodies and reagents

Western blot samples were lysed in Pierce RIPA Buffer (Thermo Scientific, Waltham, USA). Primary antibodies targeting Syntenin were purchased from Abcam (Cambridge, UK) and anti-CD63 antibodies were from SBI (Palo Alto, California). Cellular proteins were stained using anti-Calnexin (BD Biosciences, San Jose, California) and anti-GAPDH antibodies (Acris Antibodies, Herford, Germany). Secondary antibodies (anti-mouse IgG Peroxidase and anti-rabbit IgG Peroxidase) were purchased from Sigma-Aldrich (St. Louis, Missouri). EVs were removed from 1:2 diluted FCS (Gibco, Dreieich, Germany) by consecutive centrifugation (5 min, 2000 g, RT), 0.45  $\mu$ m and 100 kDa filtration.

#### HDV production

Huh7 cells were transfected with HDV-encoding plasmid pSVL(D3) [28] and HBV-surface protein-encoding plasmid pT7HB2.7 [29]. Transfection was performed with FuGENE<sup>®</sup> HD Transfection Reagent (Promega, Madison, USA). The supernatant was collected for 2 weeks, purified with HiTrap Heparin HP affinity columns (GE Healthcare, Chalfont St Giles, UK) and subsequently concentrated via centrifugation in Vivaspin<sup>®</sup> Turbo 15 columns (MWCO 50 kDa) (Sartorius, Göttingen, Germany). HDV genome equivalents were determined via RT-qPCR.

#### HDV infection

NTCP-expressing hepatoma cell lines (HepG2-NTCP or Huh7-NTCP cells) were infected with HDV at MOI of 25 vp/cell under the conditions described for HBV infection [13] and maintained in advanced DMEM (Gibco, Dreieich, Germany) supplemented with EV-free FCS, 2 mM L-Glutamine, 100 Units/ml Penicillin and 10  $\mu$ g/ml Streptomycin. EV-containing supernatants were collected for 2 weeks from day 3 post-infection (p.i.) and a fresh medium was provided every other day.

#### Purification of EVs

Apoptotic bodies were removed by centrifugation of the supernatants collected (1000  $\times$  g, 5 min) and a 0.45  $\mu$ m filtration step before EVs were purified. EVs were purified by size exclusion chromatography using qEVoriginal columns (Izon Science, Oxford, UK) according to the manufacturer's protocol and stored at -80°C. Quality of EV preparations was confirmed in Dynamic Light scattering (DLS) by dynamic light scattering, Western Blot and electron microscopy (Suppl. Fig. 2) according to the recommendations of the International Society for Extracellular Vesicles (MISEV2018) [30].

#### HDV RNA detection in EVs

EV RNA cargo was isolated using Total Exosome RNA and Protein Isolation Kit (Invitrogen, Carlsbad, California) according to the manufacturer's protocol and stored at -80°C. The presence of HDV RNA was shown by nested PCR and subsequent agarose gel electrophoresis as described [31].

#### Dynamic light scattering

Particle measurements were performed by dynamic light scattering (DLS) using a Zetasizer Nano ZS machine (ZEN3600, Malvern, Kassel, Germany) with detection at an angle of 173° (back-scattering). Samples were diluted 1:10 in 10 mM dust-free NaCl and measured in disposable, low-volume cuvettes (Malvern). For each sample, 3 measurements were run consecutively, each one for 50 $\times$ 10 s at 20°C (10 min between individual measurements) and measurements were averaged for analysis. Instrument settings were

set to automatic attenuation and automatic positioning. For all EV measurements, a Refractive Index of 1.39 and a sample absorption of 0.01 was assumed. High measurement quality was assured by analyzing raw correlation data, resulting correlation fits and polydispersity indices.

### **Isolation and activation of human immune cells**

Peripheral blood mononuclear cells (PBMC) were isolated by Biocoll (Merck, Darmstadt, Germany) based density centrifugation of heparinized blood from healthy human donors after informed consent and approval by the local ethics committee. Monocytes were selected by adherence for 1 h at 37°C in serum-free medium and differentiated into macrophages in RPMI supplied with 10 % FCS, 2 mM L-Glutamine, 100 Units/ml Penicillin, 10 µg/ml Streptomycin, amino acids, sodium pyruvate and 50 ng/ml human macrophage-colony stimulating factor (mCSF) (PeproTech, Hamburg, Germany). The medium was exchanged after 5 days and macrophages were detached with 5 mM EDTA in PBS on day 7. Macrophages were re-seeded at 10<sup>5</sup> cells/well on a 96-well plate in medium supplied with EV-free human serum and rested overnight prior to immune stimulation, PBMC were seeded at 3\*10<sup>5</sup> cells/well and stimulated the same day. For immune stimulation, primary human immune cells were incubated with EVs normalized to the number of secreting cells and supernatants were harvested 24 h post-stimulation. Release of human cytokines was determined by ELISA according to the manufacturer's instructions (BD Biosciences, Heidelberg, Germany for TNF and Invitrogen, Schwerte, Germany for IL-6 and IFN-γ).

### **Electron Microscopy**

Negative stain transmission electron microscopy (TEM) of EVs was performed on a JEOL JEM-1400 Plus microscope (camera: JEOL CCD Ruby, 8 Mpix), operating at 120 kV with a 60.000X magnification (0.275 nm/pix). For staining, the side blotting method was followed. A continuous carbon film-coated 400 mesh copper grid was treated by glow discharge for the 30 s. 5 µl of a 0.1 mg/ml EV-containing suspension was loaded on the grid and allowed to adsorb for 5 min. The liquid was pulled off by pressing filter paper (Whatman, grade 1) against the grid edge. The specimen was immediately stained with 5 µl of a filtered 2% uranyl acetate (UA) solution for the 30 s. After completely removing the excess UA solution with filter paper, the grid was allowed to dry at room temperature before TEM measurements.

### **Funding Statement**

Stephanie Jung was supported by a postdoctoral fellowship of the presidential fund of the Helmholtz Association. The study was supported by the German Research Association (DFG) via transregional collaborative research center TRR179.

### **Acknowledgements**

The Authors thank Theresa Asen for taking blood samples and excellent technical support, Adalbert Krawczyk, Hrvoje Mijocevic and Dieter Hoffmann for providing patient sera, Michael Roggendorf and Daniela Stadler for fruitful discussions and voluntary blood donors for providing blood.

### **Ethics Statement**

The use of human blood was approved by the local ethical board of the Klinikum rechts der Isar and written informed consent was obtained from all participants.



## Citations

- [1] Takahisa Kouwaki et al. "Extracellular Vesicles Deliver Host and Virus RNA and Regulate Innate Immune Response". In: *International Journal of Molecular Sciences* 18.3 (2017), p. 666. URL: <https://www.ncbi.nlm.nih.gov/pubmed/28335522>.
- [2] Vedashree Ramakrishnaiah et al. "Exosome-mediated transmission of hepatitis C virus between human hepatoma Huh7.5 cells". In: *Proceedings of the National Academy of Sciences* 110.32 (2013), pp. 13109–13113. DOI: 10.1073/pnas.1221899110. URL: <https://doi.org/10.1073/pnas.1221899110>.
- [3] Terence N. Bukong et al. "Exosomes from Hepatitis C Infected Patients Transmit HCV Infection and Contain Replication Competent Viral RNA in Complex with Ago2-miR122-HSP90". In: *PLOS pathogens* 10.10 (2014), e1004424. URL: <https://www.ncbi.nlm.nih.gov/pubmed/25275643>.
- [4] Brennetta J. Crenshaw et al. "Exosome Biogenesis and Biological Function in Response to Viral Infections". In: *The Open Virology Journal* 12 (2018), pp. 134–148. URL: <https://www.ncbi.nlm.nih.gov/pubmed/30416610>.
- [5] Luan Felipe Botelho-Souza et al. "Hepatitis delta: virological and clinical aspects". In: *Virology Journal* 14.1 (2017), p. 177. URL: <https://www.ncbi.nlm.nih.gov/pubmed/28903779>.
- [6] Dulce Alfaiate et al. "HDV RNA replication is associated with HBV repression and interferon-stimulated genes induction in super-infected hepatocytes". In: *Antiviral Research* 136 (2016), pp. 19–31. URL: <https://www.ncbi.nlm.nih.gov/pubmed/27771387>.
- [7] Katja Giersch et al. "Hepatitis Delta co-infection in humanized mice leads to pronounced induction of innate immune responses in comparison to HBV mono-infection". In: *Journal of Hepatology* 63.2 (2015), pp. 346–353. URL: <https://www.ncbi.nlm.nih.gov/pubmed/25795587>.
- [8] Chul-Yong Park et al. "Hepatitis delta virus large antigen sensitizes to TNF- $\alpha$ -induced NF- $\kappa$ B signaling". In: *Molecules and Cells* 28.1 (2009), pp. 49–55. URL: <https://www.ncbi.nlm.nih.gov/pubmed/19711042>.
- [9] V. Williams et al. "Large hepatitis delta antigen activates STAT-3 and NF- $\kappa$ B via oxidative stress". In: *Journal of Viral Hepatitis* 19.10 (2012), pp. 744–753. URL: <https://www.ncbi.nlm.nih.gov/pubmed/22967106>.
- [10] Michael Roggendorf et al. "New developments for prophylactic and therapeutic vaccines against HDV". In: *Hepatitis D. Virology, Management and Methodology, Il Pensiero Scientifico* 16 (2019), pp. 279–294.
- [11] Lester Suárez-Amarán et al. "A new HDV mouse model identifies mitochondrial antiviral signaling protein (MAVS) as a key player in IFN- $\beta$  induction". In: *Journal of Hepatology* 67.4 (2017), pp. 669–679. URL: <https://www.ncbi.nlm.nih.gov/pubmed/28527664>.
- [12] Zhenfeng Zhang et al. "Hepatitis D virus replication is sensed by MDA5 and induces IFN- $\beta$ / $\lambda$  responses in hepatocytes". In: *Journal of Hepatology* 69.1 (2018), pp. 25–35. URL: <https://www.ncbi.nlm.nih.gov/pubmed/29524530>.
- [13] Chunkyu Ko et al. "Hepatitis B virus genome recycling and de novo secondary infection events maintain stable cccDNA levels". In: *Journal of Hepatology* 69.6 (2018), pp. 1231–1241. URL: <https://www.ncbi.nlm.nih.gov/pubmed/30142426>.
- [14] Oliver Krenkel and Frank Tacke. "Liver macrophages in tissue homeostasis and disease". In: *Nature Reviews Immunology* 17.5 (2017), pp. 306–321. URL: <https://www.ncbi.nlm.nih.gov/pubmed/28317925>.
- [15] Evangelos Triantafyllou et al. "The Role of Monocytes and Macrophages in Acute and Acute-on-Chronic Liver Failure". In: *Frontiers in Immunology* 9 (2018), p. 2948. URL: <https://www.ncbi.nlm.nih.gov/pubmed/30619308>.
- [16] Oscar P. B. Wiklander et al. "Extracellular vesicle in vivo biodistribution is determined by cell source, route of administration and targeting". In: *Journal of Extracellular Vesicles* 4 (2015), p. 26316. URL: <https://www.ncbi.nlm.nih.gov/pubmed/25899407>.
- [17] Maike E. Van Hezel et al. "The Ability of Extracellular Vesicles to Induce a Pro-Inflammatory Host Response". In: *International Journal of Molecular Sciences* 18.6 (2017), p. 1285. URL: <https://www.ncbi.nlm.nih.gov/pubmed/28621719>.
- [18] Marlène Dreux et al. "Short-Range Exosomal Transfer of Viral RNA from Infected Cells to Plasmacytoid Dendritic Cells Triggers Innate Immunity". In: *Cell Host & Microbe* 12.4 (2012), pp. 558–570. URL: <https://www.ncbi.nlm.nih.gov/pubmed/23084922>.
- [19] Gavin C. Sampey et al. "Exosomes from HIV-1-infected Cells Stimulate Production of Pro-inflammatory Cytokines through Trans-activating Response (TAR) RNA". In: *The Journal of Biological Chemistry* 291.3 (2016), pp. 1251–1266. URL: <https://www.ncbi.nlm.nih.gov/pubmed/26553869>.
- [20] Zongdi Feng et al. "Human pDCs preferentially sense enveloped hepatitis A virions". In: *The Journal of Clinical Investigation* 125.1 (2015), pp. 169–176. URL: <https://www.ncbi.nlm.nih.gov/pubmed/25415438>.
- [21] Takahisa Kouwaki et al. "Extracellular Vesicles Including Exosomes Regulate Innate Immune Responses to Hepatitis B Virus Infection". In: *Frontiers in Immunology* 7 (2016), p. 335. URL: <https://www.ncbi.nlm.nih.gov/pubmed/27630638>.
- [22] Yinli Yang et al. "Exosomes mediate hepatitis B virus (HBV) transmission and NK-cell dysfunction". In: *Cellular & Molecular Immunology* 14.5 (2017), pp. 465–475. URL: <https://www.ncbi.nlm.nih.gov/pubmed/27238466>.
- [23] Masatoshi Kakizaki et al. "The immunological function of extracellular vesicles in hepatitis B virus-infected hepatocytes". In: *PLOS One* 13.12 (2018), e0205886. URL: <https://www.ncbi.nlm.nih.gov/pubmed/30596665>.
- [24] Helena Costa Verdera et al. "Cellular uptake of extracellular vesicles is mediated by clathrin-independent endocytosis and macropinocytosis". In: *Journal of Controlled Release* 266 (2017), pp. 100–108. URL: <https://www.ncbi.nlm.nih.gov/pubmed/28919558>.
- [25] Wendy Fitzgerald et al. "Extracellular vesicles generated by placental tissues ex vivo: A transport system for immune mediators and growth factors". In: *American Journal of Reproductive Immunology* 80 (2018), e12860. URL: <https://www.ncbi.nlm.nih.gov/pubmed/29726582>.
- [26] Zhijian Cai et al. "Immunosuppressive exosomes from TGF- $\beta$ 1 gene-modified dendritic cells attenuate Th17-mediated inflammatory autoimmune disease by inducing regulatory T cells". In: *Cell Research* 22.3 (2012), pp. 607–610. URL: <https://www.ncbi.nlm.nih.gov/pubmed/22157651>.
- [27] A. Bridgeman et al. "Viruses transfer the antiviral second messenger cGAMP between cells". In: *Science* 349.6253 (2015), pp. 1228–1232. URL: <https://www.ncbi.nlm.nih.gov/pubmed/26229117>.
- [28] M Y Kuo, M Chao, and J Taylor. "Initiation of replication of the human hepatitis delta virus genome from cloned DNA: role of delta antigen". In: *Journal of Virology* 63.5 (1989), pp. 1945–1950. doi: 10.1128/jvi.63.5.1945-1950.1989. URL: <https://doi.org/10.1128/jvi.63.5.1945-1950.1989>.

- [29] C Sureau, B Guerra, and H Lee. "The middle hepatitis B virus envelope protein is not necessary for infectivity of hepatitis delta virus." In: *Journal of Virology* 68.6 (1994), pp. 4063–4066. DOI: 10.1128/jvi.68.6.4063-4066.1994. URL: <https://doi.org/10.1128/jvi.68.6.4063-4066.1994>.
- [30] Clotilde Théry et al. "Minimal information for studies of extracellular vesicles 2018 (MISEV2018): a position statement of the International Society for Extracellular Vesicles and update of the MISEV2014 guidelines". In: *Journal of Extracellular Vesicles* 7.1 (2018), p. 1535750. DOI: 10.1080/20013078.2018.1535750. URL: <https://doi.org/10.1080/20013078.2018.1535750>.
- [31] G. A. Niro et al. "The predominance of hepatitis delta virus genotype I among chronically infected Italian patients". In: *Hepatology* 25:3 (1997), pp. 728–734.