

1-1-2020

## The $\alpha v\beta 6$ integrin in cancer cell-derived small extracellular vesicles enhances angiogenesis.

Shiv Ram Krishn  
*Thomas Jefferson University*

Israa Salem  
*Thomas Jefferson University*

Fabio Quaglia  
*Thomas Jefferson University*

Nicole M Naranjo  
*Thomas Jefferson University*

Ekta Agarwal  
*The Wistar Institute*

Follow this and additional works at: <https://jdc.jefferson.edu/cbfp>

*See next page for additional authors*

**[Let us know how access to this document benefits you](#)**

---

### Recommended Citation

Krishn, Shiv Ram; Salem, Israa; Quaglia, Fabio; Naranjo, Nicole M; Agarwal, Ekta; Liu, Qin; Sarker, Srawasti; Kopenhaver, Jessica; McCue, Peter A; Weinreb, Paul H; Violette, Shelia M; Altieri, Dario C; and Languino, Lucia R, "The  $\alpha v\beta 6$  integrin in cancer cell-derived small extracellular vesicles enhances angiogenesis." (2020). *Department of Cancer Biology Faculty Papers*. Paper 167.  
<https://jdc.jefferson.edu/cbfp/167>

This Article is brought to you for free and open access by the Jefferson Digital Commons. The Jefferson Digital Commons is a service of Thomas Jefferson University's [Center for Teaching and Learning \(CTL\)](#). The Commons is a showcase for Jefferson books and journals, peer-reviewed scholarly publications, unique historical collections from the University archives, and teaching tools. The Jefferson Digital Commons allows researchers and interested readers anywhere in the world to learn about and keep up to date with Jefferson scholarship. This article has been accepted for inclusion in Department of Cancer Biology Faculty Papers by an authorized administrator of the Jefferson Digital Commons. For more information, please contact: [JeffersonDigitalCommons@jefferson.edu](mailto:JeffersonDigitalCommons@jefferson.edu).

---

**Authors**

Shiv Ram Krishn, Israa Salem, Fabio Quaglia, Nicole M Naranjo, Ekta Agarwal, Qin Liu, Srawasti Sarker, Jessica Kopenhaver, Peter A McCue, Paul H Weinreb, Shelia M Violette, Dario C Altieri, and Lucia R Languino

RESEARCH ARTICLE



# The $\alpha\beta6$ integrin in cancer cell-derived small extracellular vesicles enhances angiogenesis

Shiv Ram Krishn<sup>a,b</sup>, Israa Salem<sup>a,b</sup>, Fabio Quaglia<sup>a,b</sup>, Nicole M. Naranjo<sup>a,b</sup>, Ekta Agarwal<sup>c,d</sup>, Qin Liu<sup>e</sup>, Srawasti Sarker<sup>a,b</sup>, Jessica Kopenhaver<sup>b</sup>, Peter A. McCue<sup>f</sup>, Paul H. Weinreb<sup>g</sup>, Shelia M. Violette<sup>a,h</sup>, Dario C. Altieri<sup>c,d</sup> and Lucia R. Languino<sup>a,b</sup>

<sup>a</sup>Prostate Cancer Discovery and Development Program, Thomas Jefferson University, Philadelphia, USA; <sup>b</sup>Department of Cancer Biology, Sidney Kimmel Cancer Center, Thomas Jefferson University, Philadelphia, USA; <sup>c</sup>Prostate Cancer Discovery and Development Program, The Wistar Institute, Philadelphia, USA; <sup>d</sup>Immunology, Microenvironment and Metastasis Program, The Wistar Institute, Philadelphia, USA; <sup>e</sup>Molecular and Cellular Oncogenesis Program, The Wistar Institute, Philadelphia, USA; <sup>f</sup>Department of Pathology, Thomas Jefferson University, Philadelphia, USA; <sup>g</sup>Biogen Inc., Cambridge, USA; <sup>h</sup>Admirx Tx, Cambridge

## ABSTRACT

Prostate cancer (PrCa) cells crosstalk with the tumour microenvironment by releasing small extracellular vesicles (sEVs). sEVs, as well as large extracellular vesicles (LEVs), isolated via iodixanol density gradients from PrCa cell culture media, express the epithelial-specific  $\alpha\beta6$  integrin, which is known to be induced in cancer. In this study, we show sEV-mediated protein transfer of  $\alpha\beta6$  integrin to microvascular endothelial cells (human microvascular endothelial cells 1 – HMEC1) and demonstrate that *de novo*  $\alpha\beta6$  integrin expression is not caused by increased mRNA levels. Incubation of HMEC1 with sEVs isolated from PrCa PC3 cells that express the  $\alpha\beta6$  integrin results in a highly significant increase in the number of nodes, junctions and tubules. In contrast, incubation of HMEC1 with sEVs isolated from  $\beta6$  negative PC3 cells, generated by shRNA against  $\beta6$ , results in a reduction in the number of nodes, junctions and tubules, a decrease in survivin levels and an increase in a negative regulator of angiogenesis, pSTAT1. Furthermore, treatment of HMEC1 with sEVs generated by CRISPR/Cas9-mediated down-regulation of  $\beta6$ , causes up-regulation of pSTAT1. Overall, our findings suggest that  $\alpha\beta6$  integrin in cancer sEVs regulates angiogenesis during PrCa progression.

## ARTICLE HISTORY

Received 8 July 2019  
Revised 26 March 2020  
Accepted 18 April 2020

## KEYWORDS

Angiogenesis; endothelial cell; extracellular vesicle; integrin; prostate cancer; survivin

## Introduction

Among US men, prostate cancer (PrCa) is the most common malignancy and the second leading cause of cancer death [1]. To reduce mortality from PrCa, it is necessary to understand the underlying biochemical events and molecular mechanisms involved in PrCa progression. In particular, tumour angiogenesis plays a role in the progression of PrCa [2] based on findings that microvessel density in PrCa strongly correlates with Gleason grade and may predict disease progression [3]. Recent studies have focused on small extracellular vesicles (sEVs) as crucial mediators of tumour angiogenesis [4,5] and as modulators of the tumour microenvironment (TME), thereby supporting aggressive cancer [6–8].

While large extracellular vesicles (LEVs) are plasma membrane-derived extracellular vesicles (EVs) 100–1000 nm in size, recovered by a 10,000 g centrifugation step [9], the sEVs are a population of EVs recovered by a 100,000 g high-speed ultracentrifugation step, < 200

nm in size, of endosomal or non-endosomal in origin and secreted upon fusion with the plasma membrane [9–12]. The sEV subtype sediments in the light fractions of the high-speed density gradient ultracentrifugation, and it is enriched in tetra-spanins (CD9, CD63 and CD81) [11]. The sEVs carry proteins, mRNAs and miRNAs as cargo to mediate intercellular communication and modify the functional state of the recipient cells that interact with these secreted sEVs [13–15].

Integrins are transmembrane receptors that are expressed on PrCa cell-derived sEVs [6,16–19]. During tumour angiogenesis, integrins appear to play an important role in endothelial cell migration and survival [20,21]. However, the impact of PrCa cell-derived sEV-associated integrins on endothelial cells has not been explored so far. In particular, researchers have identified  $\alpha\beta6$  integrin as an epithelial-specific integrin that is not expressed in endothelial cells under normal conditions but can be induced [22–24,25]. The  $\alpha\beta6$  integrin is known

to be up-regulated in many cancers [26] and correlates with poor survival in breast cancer [27–29], non-small cell lung cancer [30] and colon cancer [31,32] patients. It is not expressed in healthy prostate but is highly expressed in primary and metastatic PrCa [33,34]. Our previous studies have shown that the PrCa cell-derived sEV-associated  $\alpha\beta6$  integrin functionally modulates cells of the prostate TME [17,19]. The  $\alpha\beta6$  integrin is actively packaged into sEVs isolated from PrCa cell lines, and is efficiently transferred via these sEVs to  $\beta6$ -negative PrCa cells or monocytes, thus resulting in increased migration of recipient PrCa cells [17] and M2 polarisation of recipient monocytes, respectively [19]. These previous studies led us to hypothesise that PrCa cell-derived sEVs that express  $\alpha\beta6$  integrin ( $\alpha\beta6$ -positive sEVs) may functionally impact endothelial cells.

In this study, we demonstrate for the first time that PrCa cell-derived  $\alpha\beta6$  integrin is transferred via sEVs as a functionally active molecule to  $\beta6$ -negative endothelial cells and significantly impact the angiogenic potential of endothelial cells. Despite the important role of angiogenesis in PrCa progression, clinical trials with anti-angiogenic therapy in this disease have not been effective [35–37]. Owing to our novel findings, targeting  $\alpha\beta6$  integrin in combination with current anti-angiogenic therapies may provide a novel approach to develop effective therapies against PrCa.

## Materials and methods

### Cell lines

Bovine aortic endothelial cells (BAECs) were cultured in Dulbecco's modified eagle medium (DMEM) supplemented with 10% foetal bovine serum (FBS), 100  $\mu\text{g}/\text{mL}$  streptomycin and 100 U/mL penicillin (Corning Cellgro, USA) in a humidified atmosphere of 5%  $\text{CO}_2$  at 37°C [38].

Human microvascular endothelial cells 1 (HMEC1) were cultured in endothelial cell growth media supplemented with endothelial cell growth supplement (R&D Systems, Cat. # CCM027), 100  $\mu\text{g}/\text{mL}$  streptomycin and 100 U/mL penicillin (Corning Cellgro, USA) in a humidified atmosphere of 5%  $\text{CO}_2$  at 37°C.

C4-2B cell lines were maintained in Roswell park memorial institute (RPMI) media with L-glutamine (Corning, USA) supplemented with 5% FBS, 1 mM sodium pyruvate (Corning Cellgro, USA), non-essential amino acids (Corning Cellgro, USA), 100  $\mu\text{g}/\text{mL}$  streptomycin and 100 U/mL penicillin (Corning Cellgro, USA) in a humidified atmosphere of 5%  $\text{CO}_2$  at 37°C. The C4-2B PrCa cells stably transfected with

either empty vector (C4-2B-Mock) or  $\beta6$  cDNA-expression vector (C4-2B- $\alpha\beta6$ ) were maintained as previously described [33].

PC3 cell lines were maintained in RPMI media with L-glutamine (Corning, USA) supplemented with 10% FBS, 100  $\mu\text{g}/\text{mL}$  streptomycin and 100 U/mL penicillin (Corning Cellgro, USA) in a humidified atmosphere of 5%  $\text{CO}_2$  at 37°C. PC3 cells stably transfected with control shRNA (PC3-shCtrl) or shRNA specifically targeting  $\beta5$  integrin subunit (PC3-sh $\beta5$ ) or  $\beta6$  integrin subunit (PC3-sh $\beta6$ ) were maintained as previously described [33,39].

For genomic depletion of the  $\beta6$  integrin subunit, PC3 cells were transfected with pX458 (Addgene plasmid #48,138), a plasmid expressing eGFP, spCas9 and a sgRNA targeting the fifth coding exon of  $\beta6$  integrin (seed sequence: 5'-GCTAATATTGACACCCCGA-3') using Lipofectamine LTX with Plus Reagent (ThermoFisher Scientific, Waltham, Massachusetts). At 72 h after transfection, eGFP-positive cells were single-cell sorted by a FACSria II flow cytometer (BD Biosciences, San Jose, California). Clonally expanded cell populations were screened for frame-shifting indels by amplifying the target locus by polymerase chain reaction (PCR) (forward primer: 5'-CAGTGAGATTCATAGCTGAGTTGCAG-3'; reverse primer: 5'-GTAGAGACAGCAAACCTCCGAAGC-3') and Sanger sequenced using both forward and reverse primers above. Complete knockout was confirmed in PC3-WT-clone 1, PC3- $\beta6$  KO-clone 5, PC3- $\beta6$  KO-clone 7 cells by immunoblotting (IB) using an antibody (Ab) to the  $\alpha\beta6$  integrin.

### Antibodies for immunoblotting

The following primary Abs were used for IB analyses: mouse monoclonal Abs against: ALIX (Abcam, ab117600),  $\alpha\beta6$  integrin (6.2A1) [40], CD9 (Santa Cruz, sc18869), CD63 (Abcam, ab8219), CD81 (Abcam, ab23505); rabbit polyclonal Abs against: actin (Sigma Aldrich, A2066), CANX (Santa Cruz, sc-11,397), STAT1 (Santa Cruz, sc-346), TSG101 (Abcam, ab30871); and rabbit monoclonal Abs against integrin  $\beta5$  subunit (Cell Signaling, 3629), pSTAT1(Y701) (Cell Signaling, 7649 S) and survivin (Cell Signaling, 2808). The following secondary Abs were used for IB analyses: HRP-linked anti-mouse IgG (Cell Signaling, 7076 S) and HRP-linked anti-rabbit IgG (Cell Signaling, 7074 S).

### LEV and sEV isolation and analysis

LEVs included large and intermediate EVs and were isolated, as described previously [5,11]. Briefly, PrCa

cells (PC3-parental) were plated in 150 mm cell culture dishes (ThermoScientific) in their respective cell line complete media. After 48 h of incubation at 37°C, cells were transferred to starvation media (complete media devoid of FBS) for the next 48 h. LEVs were isolated from culture supernatant (SN) collected after 48 h of serum starvation by differential centrifugation. Briefly, the dead cells and cell debris were spun down from SN at 2000 g, 4°C for 20 min. The SN collected was spun at 10,000 g, 4°C for 35 min in a Beckman Type 45 Ti rotor using a Beckman L8-70 M Ultracentrifuge. The 10,000 g pellet was washed in phosphate buffer saline (PBS) followed by a second spin at 16,000 g, 4°C for 40 min in a tabletop centrifuge. The final LEV pellet (PC3 LEVs) was resuspended in PBS.

For sEV isolation, PrCa cells (PC3-parental, -shCtrl, -sh $\beta$ 6, -sh $\beta$ 5, -WT, - $\beta$ 6 KO-5, - $\beta$ 6 KO-7 and C4-2B-Mock, - $\alpha$ v $\beta$ 6) were plated in 150 mm cell culture dishes (ThermoScientific) in their respective complete media. After 48 h of incubation at 37°C, cells were transferred to starvation media (complete media devoid of FBS) for the next 48 h. sEVs were isolated from SN collected after 48 h of serum starvation by high-speed differential ultracentrifugation. Briefly, the dead cells and cell debris were spun down from SN at 2000 g, 4°C for 20 min. The SN collected was spun at 10,000 g, 4°C for 35 min in a Beckman Type 45 Ti rotor using a Beckman L8-70 M Ultracentrifuge. The SN collected without disturbing the 10,000 g pellet was spun at 100,000 g, 4°C for 70 min in a Beckman Type 45 Ti rotor using a Beckman L8-70 M Ultracentrifuge; the pellet was washed in PBS followed by a second spin at 100,000 g, 4°C for 70 min in a Beckman Type 45 Ti rotor using a Beckman L8-70 M Ultracentrifuge. The final sEV pellet from each cell type mentioned above was resuspended in PBS to get PC3 sEVs, PC3-shCtrl sEVs, PC3-sh $\beta$ 6 sEVs, PC3-sh $\beta$ 5 sEVs, PC3-WT sEVs, PC3- $\beta$ 6 KO-5 sEVs, PC3- $\beta$ 6 KO-7 sEVs, C4-2B-Mock sEVs and C4-2B- $\alpha$ v $\beta$ 6 sEVs. The total cell lysates (TCLs; 10–40  $\mu$ g), LEV or sEV lysates were prepared using radio immuno precipitation assay (RIPA) buffer (10 mM Tris-HCl, pH 7.4, 150 mM NaCl, 1 mM EDTA, 0.1% SDS, 1% Triton X-100 and 1% sodium deoxycholate) supplemented with protease inhibitors (calpain, aprotinin, leupeptin, pepstatin, sodium fluoride and sodium orthovanadate). The total protein concentration of sEVs was determined using BioRad DC<sup>TM</sup> protein assay kit as per the manufacturer's protocol. Equal amounts of proteins in non-reducing (heated without 2-mercaptoethanol) and reducing conditions (heated with 2-mercaptoethanol) were separated by sodium dodecyl sulphate-polyacrylamide gel electrophoresis (SDS-PAGE), transferred to polyvinylidene difluoride (PVDF) membranes (immobilon-E PVDF membrane, pore size

0.45  $\mu$ m, Millipore), blocked with blocking buffers [5% non-fat dry milk in Tris Buffer Saline with 0.1% Tween 20 (TBST) or 5% bovine serum albumin (BSA) in TBST] for 1 h at room temperature, incubated overnight with primary Abs as described above, followed by TBST washes (4  $\times$  10 min) at room temperature, incubation with horseradish peroxidase (HRP)-conjugated anti-mouse or -rabbit secondary Abs for 1 h at room temperature, followed by TBST washes (4  $\times$  10 min) at room temperature. For visualisation, WesternBright<sup>TM</sup> ECL HRP substrate kits (Advanta Inc., CA, USA) were used. The size distribution (mean and mode) and concentration of LEVs or sEVs were determined by nanoparticle tracking analyses (NTAs) detailed below.

### *Iodixanol density gradient*

For iodixanol density gradient separation, a previously described procedure was used [19]. Briefly, the LEVs obtained from PC3-parental cells or sEVs obtained from PC3 cells (PC3-parental, -shCtrl, -sh $\beta$ 5 and -sh $\beta$ 6) or C4-2B cells (C4-2B-Mock, - $\alpha$ v $\beta$ 6) were suspended in 1.636 mL of 30% iodixanol solution [made by mixing 1:1 of 60% (wt/vol) stock solution of iodixanol (OptiPrep<sup>TM</sup>, Sigma # 1556) with a buffer (0.25 M sucrose, 10 mM Tris pH 8.0, 1 mM EDTA, pH 7.4)] and layered at the bottom of an ultracentrifugation tube. Next, 0.709 mL of 20% (wt/vol) iodixanol and 0.654 mL of 10% (wt/vol) iodixanol solutions were successively layered on top of the 30% iodixanol-vesicle suspension to create a discontinuous gradient. Gradient samples were centrifuged for 1 h at 350,000 g, 4°C in a SW55Ti rotor using a Beckman L8-70 M Ultracentrifuge. Ten consecutive fractions of 0.267 mL were collected from top to bottom of the gradient. The refractive index of each fraction was assessed with an ABBE-3 L refractometer (Fisher Scientific) and density was calculated. All 10 fractions were diluted with 1 mL PBS and centrifuged for 70 min at 100,000 g, 4°C in a TLA-100.2 rotor using a Beckman, Optima TL Ultracentrifuge. The pellets thus obtained in 10 respective fractions were again washed in 1 mL PBS and centrifuged for 70 min at 100,000 g, 4°C in a TLA-100.2 rotor using a Beckman, Optima TL Ultracentrifuge. The final pellet in each fraction was resuspended in 30  $\mu$ L of PBS and stored at -80°C or utilised for analysis by NTA or IB in non-reducing and reducing conditions or functional assays.

### *Nanoparticle tracking analysis*

The size distribution and concentration of sEVs isolated from the PrCa cells (PC3-parental, -shCtrl, -sh $\beta$ 5, -sh $\beta$ 6,

-WT, - $\beta 6$  KO-5, - $\beta 6$  KO-7, C4-2B-Mock and - $\alpha v\beta 6$  cells) were analysed using NanoSight NS300 instrument (Malvern Panalytical, UK). Briefly, sEV suspensions were diluted 1:1000 and/or 1:200 (for iodixanol density gradient separated fractions) in PBS, and the analysis was performed using camera levels ranging from 11 to 13 to see the EV particles clearly in a way that they do not appear saturated (coloured pixels). Using the script SOP standard measurement, video files of 30- or 60-s duration (repeated three times or five times) were captured with a frame rate of 25 frames per second of particles moving under Brownian motion at a temperature ranging from 22°C to 25°C. The analysis of videos was performed at a detection threshold ranging from 3 to 5 using NTA software version 3.1 (build 3.1.54).

### Quantitative real-time PCR

HMEC1 or BAEC ( $2 \times 10^5$ ) were seeded on six-well cell culture dishes. Next day, cells were washed with PBS, incubated with endothelial cell basal media and either PBS or sEVs (40  $\mu\text{g}/\text{mL}$ ) isolated from PC3 cells (4, 8 and 16 h for BAEC or 2, 4, 8, 16 and 24 h for HMEC1). After incubation, cells were washed with PBS, trypsinised and total RNA from HMEC1, BAEC or PC3 PrCa cells (positive control for  $\beta 6$  mRNA expression) was isolated using the Qiagen RNeasy Kits (Qiagen, Valencia, CA, USA) as per manufacturer's protocol. RNA (1  $\mu\text{g}$ ) was reverse transcribed with random hexamer oligos (Invitrogen) and SuperScript II RNase H-reverse transcriptase enzyme (Invitrogen). Subsequently, for real-time PCR analysis, complementary DNA (cDNA) was amplified using the QuantStudio 12 K Flex Real-Time PCR system. The gene expression of  $\beta 6$ , BIRC5 and GAPDH were profiled using primers for  $\beta 6$  (forward primer, 5'-GGTCTCATCTGGAAGCTACTGGTGTCA-3'; reverse primer, 5'-GGTCTCCCAGATGCACAGTAGGACAACC-3'), BIRC5 (forward primer, 5'-GACTTGGCTCGATGCTGTGG-3'; reverse primer, 5'-TACGCCAGACTTCAGCCCTG-3') and GAPDH (forward primer, 5'-GGGAAGGTGAAGGTCCGAGT-3'; reverse primer, 5'-GTTCTCAGCCTTGACGGTGC-3'). The relative mRNA expression was calculated using the  $2^{-\Delta\Delta\text{CT}}$  method. Each reaction was carried out in triplicate; mean and standard error of mean were calculated using Excel (Microsoft) software.

### Analysis of sEV-mediated $\alpha v\beta 6$ integrin transfer and impact on angiogenic signalling via immunoblotting

To evaluate the PC3-sEV-mediated internalisation of  $\alpha v\beta 6$  integrin, the HMEC1 or BAEC ( $2 \times 10^5$ ) cultured in serum- and growth factor-starved conditions were incubated with the PBS as vehicle control or the same

dose of sEVs (20  $\mu\text{g}/\text{mL}$ ) at different time lengths (6, 16 and 24 h for HMEC1 and 4, 8 and 16 h for BAEC). The efficiency of PC3 sEV-mediated  $\alpha v\beta 6$  integrin internalisation in HMEC1 was also evaluated after acid wash [sodium acetate buffer (0.2 M acetic acid/0.5 M NaCl, pH 2.8)]. The sEV-mediated internalisation of  $\alpha v\beta 6$  integrin in HMEC1 was also tested upon incubation of HMEC1 ( $2 \times 10^5$ ) cultured in serum- and growth factor-starved conditions with 40  $\mu\text{g}/\text{mL}$  of sEVs derived from PrCa cells (PC3-WT, - $\beta 6$  KO-5 and - $\beta 6$  KO-7) for 18 h. After incubation with sEVs, HMEC1 or BAEC were washed with PBS, trypsinised, collected, lysed in RIPA buffer containing protease inhibitors and TCL were subjected to IB analysis to measure  $\beta 6$  levels.

The effect of PrCa sEVs on angiogenic signalling in HMEC1 was also evaluated after incubation of HMEC1 ( $2 \times 10^5$ ) with PBS or 40  $\mu\text{g}/\text{mL}$  sEVs derived from PrCa cells (PC3-WT, - $\beta 6$  KO-5, - $\beta 6$  KO-7, -shCtrl, -sh $\beta 6$ , -sh $\beta 5$  and C4-2B-Mock or - $\alpha v\beta 6$ ) for 18 h. After incubation with sEVs, HMEC1 were washed with PBS, trypsinised, collected, lysed in RIPA buffer containing protease inhibitors and TCL were subjected to IB analysis to measure levels of angiogenic signalling molecules.

### Analysis of sEV-mediated $\alpha v\beta 6$ integrin transfer and cell surface expression via FACS

Fluorescence-activated cell sorting (FACS) analysis was employed to detect sEV-mediated  $\alpha v\beta 6$  integrin transfer and expression on the cell surface of HMEC1. HMEC1 ( $2 \times 10^6$ ) plated in 100 mm cell culture dishes were serum- and growth factor-starved and incubated with PBS or 40  $\mu\text{g}/\text{mL}$  PC3 sEVs for 18 h. After incubation with PBS or sEVs, HMEC1 were trypsinised, washed with PBS and  $3 \times 10^5$  cells were incubated with the Ab specific to  $\alpha v\beta 6$  integrin (mAb 6.4B4, 10  $\mu\text{g}/\text{mL}$  in HMEC1 media) or mouse IgG as isotype control (10  $\mu\text{g}/\text{mL}$  in HMEC1 media) for 45 min at 4°C. Samples were washed three times with complete media (RPMI with 10% FBS), pelleted and incubated with Alexa Fluor™ 488 F(ab')<sub>2</sub> fragment of rabbit anti-mouse-IgG (H + L) (Invitrogen) in HMEC1 complete media for 30 min at 4°C, washed three times with complete media (RPMI with 10% FBS), pelleted and resuspended in 500  $\mu\text{L}$  of PBS and analysed. The data were acquired using BD Celesta flow cytometer (BD Biosciences) and analysed by FlowJo software.

### Trypan blue dye exclusion assay

HMEC1 ( $2 \times 10^5$ ) were seeded on six-well cell culture dishes (replicates  $n = 3$ ). Next day, cells were washed

with PBS, incubated with endothelial cell basal media and either PBS or iodixanol density gradient separated sEVs (40  $\mu\text{g}/\text{mL}$ ) isolated from PrCa cells (PC3-shCtrl, -sh $\beta$ 6, -sh $\beta$ 5, C4-2B-Mock and - $\alpha\text{v}\beta$ 6) at 37°C for 18 h. After 18 h of incubation with PBS or respective sEVs, HMEC1 from each condition were washed with PBS, trypsinised, collected and resuspended in endothelial cell basal media. One part of the cell suspension was mixed with one part of 0.4% trypan blue. The mixture was allowed to incubate 3 min at room temperature and 10  $\mu\text{L}$  of the trypan blue/cell mixture was applied to a haemocytometer and the unstained cells (viable) were counted using a hand tally counter in 4 separate grids (each having 16 squares) of haemocytometer using the inverted microscope under 10 $\times$  objective. The total number of viable cells per mL = (the total number of viable cells counted in 4 grids/4)  $\times$  10,000  $\times$  dilution factor. For PC3-shCtrl, -sh $\beta$ 6 and -sh $\beta$ 5 cells ( $1 \times 10^6$ ) were seeded on 100 mm cell culture dishes (replicates  $n = 3$ ) in complete media, incubated for 72 h at 37°C and after incubation, the viable cells were counted by trypan blue dye exclusion method as described above.

### Boyden chamber assay

HMEC1 ( $5 \times 10^4$ ) were seeded on Transwell chambers (replicates  $n = 3$ ) and incubated with PBS or iodixanol density gradient separated sEVs ( $0.3 \times 10^9$  vesicles) isolated from the PrCa cells (PC3-parental, -shCtrl, -sh $\beta$ 5, -sh $\beta$ 6, C4-2B-Mock and - $\alpha\text{v}\beta$ 6). To acquire the  $0.3 \times 10^9$  sEVs utilised for the functional analyses,  $\sim 12 \times 10^4$  PC3 cells and  $\sim 2 \times 10^5$  C4-2B cells are required. HMEC1 complete media were placed in the bottom chamber as a chemoattractant for sEV-incubated HMEC1 in Transwell chambers and incubated for 24 h at 37°C. In another set of experiments, HMEC1 basal media were placed in the bottom chamber for sEV-incubated HMEC1 in Transwell chambers and incubated for 24 h at 37°C. After 24 h, Transwell inserts were placed in 100% methanol for 10 min to allow the fixation of migrated HMEC1. A cotton-tipped applicator was used to remove the remaining methanol from the top of the membranes and they were allowed to dry. For staining the fixed HMEC1, the membranes were positioned in a 0.5% crystal violet solution and incubated at room temperature for 10 min. Excess crystal violet was removed from the top of the membranes with a cotton-tipped applicator. Membranes were gently rinsed in distilled water to remove the excess crystal violet. Pictures were captured underneath an inverted microscope and the number of

migrated cells was counted manually in different fields of view ( $n = 6$  or 9) to obtain an average total number of cells that have migrated through the membranes towards the chemo-attractant and attached to the underside of the membranes.

### Tube formation assay

For tube formation assays, 96-well plates were coated with 70  $\mu\text{L}$  of BD Matrigel™ Basement Membrane Matrix (Cat. #354,230). Plates were incubated for 3 h at 37°C to allow the Matrigel to form a gel. A single-cell suspension of  $1.5 \times 10^4$  HMEC1 or BAEC/well (replicates  $n = 3$ ) were plated on to the solidified Matrigel using 100  $\mu\text{L}$  media/well and incubated with PBS, or iodixanol density gradient separated sEVs ( $0.3 \times 10^9$  vesicles) isolated from the PrCa cells (PC3-shCtrl, -sh $\beta$ 5, -sh $\beta$ 6, C4-2B-Mock and - $\alpha\text{v}\beta$ 6) and incubated for 5 h for HMEC1 or 8 h for BAEC at 37°C. The endothelial tubes formed were examined after 5 h for HMEC1 or 8 h for BAEC using a light microscope and images were captured in different fields of view ( $n = 6$ ). Using the ImageJ Angiogenesis Analyser Plugin, the photomicrographs were analysed and quantified for nodes, junctions and tubules formed.

### Human tissue specimens

All formalin-fixed and paraffin-embedded human tissue specimens used in this study were de-identified and processed in accordance with IRB approved protocols. Seven metastatic prostate adenocarcinoma tissue samples (Gleason Score [GS] 8 [ $n = 1$ ], GS 9 [ $n = 2$ ], GS 10 [ $n = 4$ ]) were obtained from the Department of Pathology at Thomas Jefferson University (Philadelphia, PA). Additionally, nine human malignant prostate adenocarcinomas tissue samples (GS 7 [ $n = 5$ ], GS 8 [ $n = 2$ ], GS 9 [ $n = 1$ ] and GS 10 [ $n = 1$ ]) were obtained from the Cooperative Human Tissue Network (CHTN) western division at Vanderbilt University Medical Centre, TN, or Mid-Atlantic division at University of Virginia, VA. The CHTN is funded by the National Cancer Institute and other investigators may have received specimens from the same subjects.

### Immunohistochemistry (IHC)

Following a standardised protocol, immunohistochemistry (IHC) was performed on the PrCa tissue sections. The tissue sections were baked at 60°C for 1 h, followed by deparaffinisation with xylene (3 min  $\times$  2), rehydration with graded alcohols (100%, 90%, 70%, 50% and

30% for 3 min each) followed by deionised water (3 min  $\times$  2). The sections were incubated with 3% H<sub>2</sub>O<sub>2</sub> solution for quenching endogenous peroxidase activity, followed by antigen retrieval by pepsin (0.5% in 5 mM HCl) digestion for  $\alpha$ v $\beta$ 6 integrin for 15 min at 37°C or proteinase K (20  $\mu$ g/mL in Tris-EDTA buffer, pH 8.0) digestion for von Willebrand factor (vWF) for 15 min at 37°C or sodium citrate buffer (10 mM sodium citrate, 0.05% Tween 20, pH 6.0) for CD31 for 15 min at 95°C. Sections were washed once with deionised water for 5 min, followed by PBS wash for 5 min and blocked with 5% goat serum or horse serum made in PBS with 0.1% Tween 20 (PBST) for 2 h. The tissue sections were incubated overnight at 4°C with an Ab to  $\alpha$ v $\beta$ 6 integrin (6.2A1, 2  $\mu$ g/mL) or isotype control mouse-IgG (mIgG, 2  $\mu$ g/mL), vWF (Dako A0082, 3  $\mu$ g/mL) or isotype control rabbit-IgG (rbIgG, 3  $\mu$ g/mL) and CD31 (ab28364, 1  $\mu$ g/mL) or isotype control rabbit-IgG (rbIgG, 1  $\mu$ g/mL). The following day, the tissue sections were washed with PBST (5 min  $\times$  2) followed by PBS (5 min) and incubated with secondary Ab in PBST (biotinylated horse anti-mouse-IgG [BA-2000, Vector Laboratories, Burlingame, CA] or biotinylated goat anti-rabbit-IgG [BA-1000, Vector Laboratories, Burlingame, CA], 10  $\mu$ g/mL) for 30 min at room temperature. The unbound secondary Ab was washed with PBST (5 min  $\times$  2), followed by PBS (5 min). The tissue sections were incubated with streptavidin horseradish peroxidase (SAP) in PBS (SA-5004, Vector Laboratories, Burlingame, CA, 5  $\mu$ g/mL) for 30 min at room temperature. The unbound SAP was washed with PBST (5 min  $\times$  2), followed by PBS (5 min). The colour was developed by adding substrate chromogen, 3,3'-diaminobenzidine solution (DAB peroxidase substrate kit, SK-4100, Vector Laboratories, Burlingame, CA). A brown precipitate indicated positive expression. The DAB reaction was stopped by rinsing the tissue sections in deionised water. The sections were counterstained with Harris haematoxylin, dehydrated in graded ethanol (30%, 50%, 70%, 90% and 100% for 5 min each) followed by xylene (5 min  $\times$  2), dried and finally mounted with Permount (Vector Laboratories, Burlingame, CA).

At least two members of the team reviewed each tumour section. The immunostaining intensity of  $\alpha$ v $\beta$ 6 integrin in PrCa epithelial cells or vWF, CD31 in endothelial cells within each specimen was evaluated by the pathologist and given a score. The scoring of immunostaining intensity is summarised and grouped as follows: negative, 0; negligible, 1+; weak, 2+ and strong, 3+. For a given intensity, the percentage of PrCa cells positive for  $\alpha$ v $\beta$ 6 integrin within a given

specimen was also scored on a scale of 0–100: 0%, no cell staining; 100%, all cells positively stained.

### Statistical analysis

For statistical analysis, Student's t-test is used for comparing two group means. One-way ANOVA with post hoc Fisher's LSD test are applied to compare the means of three or more independent groups. A two-sided *P* value of  $\leq 0.05$  is considered statistically significant. Software GraphPad Prism 7 is used for data analysis.

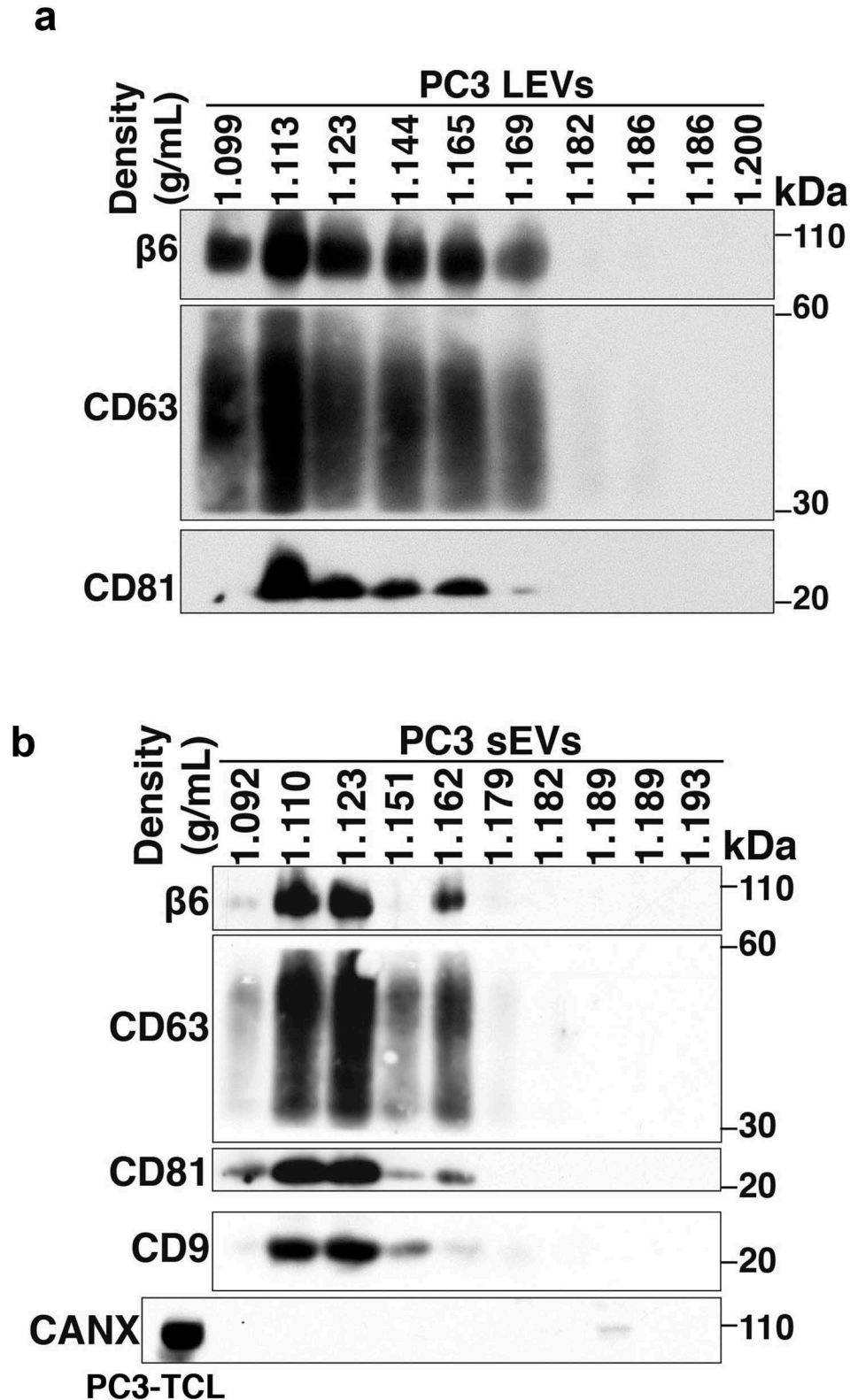
## Results

### Characterisation of prostate cancer cell-derived $\alpha$ v $\beta$ 6-positive LEVs and $\alpha$ v $\beta$ 6-positive sEVs

EV subtypes include LEVs that are 100–1000 nm in size and sEVs that are  $< 200$  nm size [11]. These EV subtypes can be isolated by flotation into iodixanol density gradients on the basis of different buoyant densities and sizes [11]. We have previously shown that  $\alpha$ v $\beta$ 6 integrin is enriched in sEVs derived from PrCa cells. We now also show the expression of  $\alpha$ v $\beta$ 6 integrin in LEVs. We utilised serum-starved conditioned media from PrCa cells (PC3 cells) endogenously expressing  $\alpha$ v $\beta$ 6 integrin for isolation of LEVs by differential centrifugation (10,000 *g*). LEVs were then floated on an iodixanol density gradient and 10 fractions were collected from top to bottom. Our IB analysis shows that  $\beta$ 6 and tetraspanins (CD63 and CD81) are expressed in iodixanol density gradient fractions (density range: 1.099–1.169 g/mL) from PC3-derived LEV samples (Figure 1a). A previous study has also shown expression of tetraspanins like CD81 in LEVs at varying levels [41], although in one study, it was shown that expression of CD81 in LEVs is lower than sEVs [42].

After removal of LEVs, sEVs were isolated by high-speed differential ultracentrifugation (100,000 *g*) followed by flotation on an iodixanol density gradient. We analyse the levels of the  $\beta$ 6 and sEV markers (CD63, CD81 and CD9) in each iodixanol density gradient fraction from the PC3-derived sEV samples and observed that their levels are the highest in the 1.123 g/mL density fraction (Figure 1b). None of the 10 iodixanol density gradient fractions shows the expression of Calnexin (CANX), an endoplasmic reticulum (ER) marker known to be absent in sEVs which is instead detected in PC3-total cell lysates (PC3-TCL) (Figure 1b). Our proteomic analysis of PC3 sEVs [19] had shown that several aberrations follow down-





**Figure 1.** Characterisation of prostate cancer cell-derived  $\alpha\beta$ 6-positive LEVs and  $\alpha\beta$ 6-positive sEVs.

(a) Iodixanol density gradient analysis of PC3 cell-derived large extracellular vesicles (PC3 LEVs) was performed as described in the Materials and methods. Expression of  $\beta$ 6 integrin subunit, CD63 and CD81 analysed by immunoblotting (IB) (non-reducing conditions) in LEV lysates of 10 consecutive iodixanol density gradient fractions is shown. (b) Iodixanol density gradient analysis of PC3 cell-derived small extracellular vesicles (PC3 sEVs) was performed as described in the Materials and methods. IB analysis for expression of  $\beta$ 6 integrin subunit, CD63 and CD81 (non-reducing conditions) and CD9 (reducing conditions) in sEV lysates of 10 consecutive iodixanol density gradient fractions is shown. IB of CANX (reducing conditions) in PC3-total cell lysates (PC3-TCL) and sEV lysates of 10 consecutive fractions is shown. Different gels were used to separate samples under reducing or non-reducing conditions

regulation of  $\alpha\text{v}\beta 6$  integrin and indicated that these aberrant sEVs might impact endothelial cell behaviour [19]. Given our results showing that the levels of  $\alpha\text{v}\beta 6$  integrin and sEV markers are the highest in the 1.123 g/mL fraction, we used this fraction [11] to narrow down the subset that carries the functional  $\alpha\text{v}\beta 6$  integrin and its downstream effectors.

### **Prostate cancer cell-derived small extracellular vesicular- $\alpha\text{v}\beta 6$ integrin is transferred to endothelial cells**

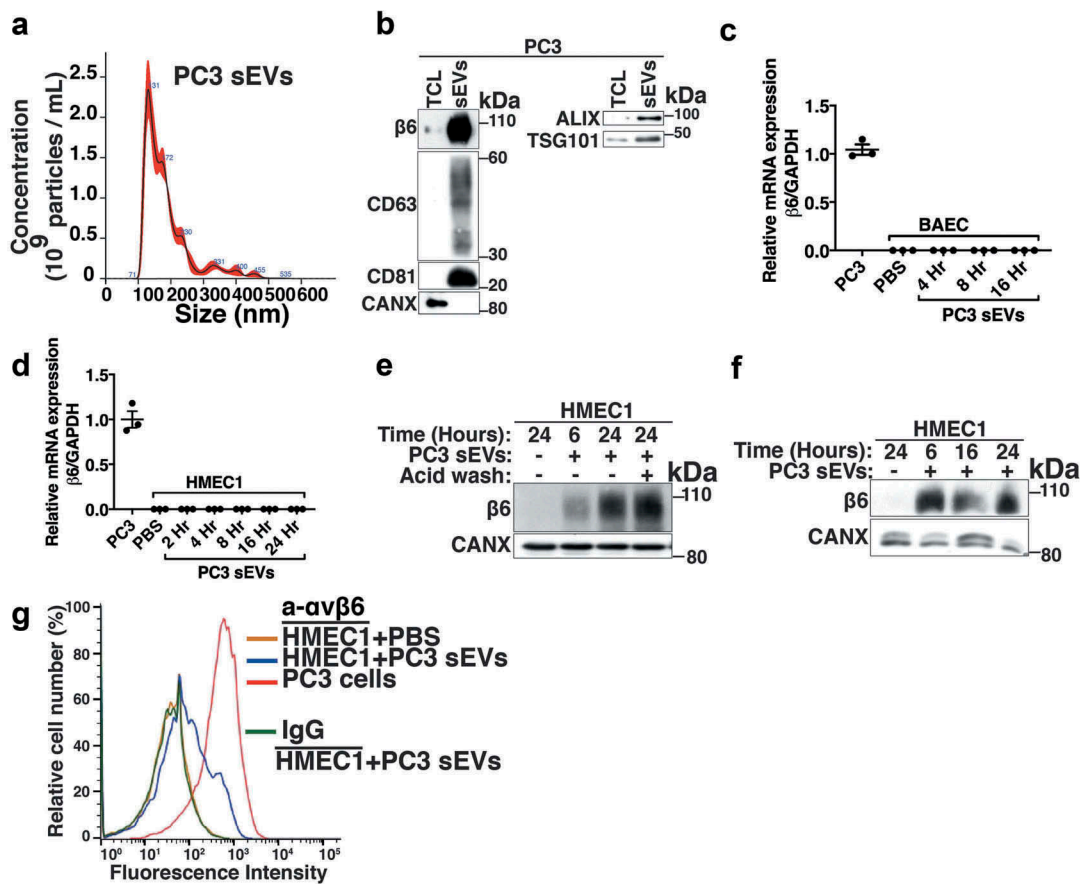
Endothelial cells are an important component of the prostate TME and their role in increased angiogenesis has been associated with prostate tumour progression [2,3]. We have previously shown that the  $\alpha\text{v}\beta 6$  integrin is packaged in sEVs shed by PrCa cells, transferred via sEVs to recipient prostate cells and monocytes, and is able to functionally modulate these cells [17,19]. We hypothesised that transfer of PrCa cell-derived sEVs that express  $\alpha\text{v}\beta 6$  integrin ( $\alpha\text{v}\beta 6$ -positive sEVs) to  $\beta 6$ -negative endothelial cells might promote the angiogenic potential of these recipient endothelial cells.

To study PrCa cell-derived sEV-mediated transfer of  $\alpha\text{v}\beta 6$  integrin to endothelial cells, we selected human microvascular endothelial cells (HMEC1) and bovine aortic endothelial cells (BAEC) that do not express  $\beta 6$ . To investigate whether  $\alpha\text{v}\beta 6$  integrin is transferred to endothelial cells via iodixanol density gradient isolated sEVs, we first collected the 100,000 g pellet and characterised it by NTA and IB (Figure 2a,b). Then we isolated them using iodixanol density gradient as described in the previous section. Our NTA shows that the sEVs from PC3 cells have a diameter of < 150 nm, confirming their vesicular subtype identification as sEVs (Figure 2a). The 100,000 g pellet is also characterised for expression of sEV-specific markers by IB; sEVs from PC3 cells show enrichment of  $\beta 6$  and sEV markers CD63, CD81, ALIX and TSG101 compared to TCL (Figure 2b). Furthermore, the sEVs do not express CANX, an ER marker known to be present in TCL (Figure 2b). Incubation of BAEC and HMEC1 with PBS or  $\alpha\text{v}\beta 6$ -positive sEVs from PC3 cells for different time points (4, 8 and 16 h for BAEC and 2, 4, 8, 16 and 24 h for HMEC1) shows that  $\beta 6$  mRNA expression is not induced in endothelial cells (Figure 2c,d). To test whether  $\alpha\text{v}\beta 6$  integrin is transferred as protein via sEVs to endothelial cells, we incubated HMEC1 and BAEC with PBS or 100,000 g isolated  $\alpha\text{v}\beta 6$ -positive sEVs from PC3 cells for different time periods [6, 24 h for HMEC1 (Figure 2e,f) and 4, 8, 16 h for BAEC

(Fig. S1)]. We observe that a low level of  $\beta 6$  integrin subunit is transferred in 6 h while a more robust amount is transferred in 24 h in HMEC1 (Figure 2e). While in BAEC, a low level of  $\beta 6$  integrin subunit is transferred in as few as 4 h, a more robust amount is transferred in 8 h (Fig. S1). Furthermore, the results show that after sEV incubation, acid wash (which removes non-specifically trapped proteins from the cell surface) of recipient HMEC1 does not reduce  $\beta 6$  levels transferred to HMEC1, indicating an efficient microvascular endothelial cell internalisation of the transferred  $\beta 6$  integrin subunit (Figure 2e). These results were confirmed using iodixanol density gradient isolated  $\alpha\text{v}\beta 6$ -positive sEVs and show that incubation of HMEC1 with the  $\beta 6$ -positive sEV fraction, corresponding to 1.123 g/mL density, exhibits a very efficient transfer of  $\beta 6$  integrin subunit to HMEC1 in as little as 6 h (Figure 2f). Since the  $\alpha\text{v}\beta 6$  integrin is a cell-surface receptor, we further evaluated *de novo* cell-surface expression of  $\alpha\text{v}\beta 6$  integrin after transfer via sEVs into HMEC1. Using FACS analyses, we show that upon incubation with PC3 sEVs, the  $\alpha\text{v}\beta 6$  integrin is transferred to HMEC1 and detected on the cell surface (Figure 2g). Overall, our data show that *de novo* expression of  $\alpha\text{v}\beta 6$  integrin on the plasma membrane of endothelial cells can be attributed to efficient protein transfer via PC3 sEVs.

### **$\alpha\text{v}\beta 6$ integrin in sEVs does not affect expression of sEV markers**

To more specifically evaluate the functional implications of  $\alpha\text{v}\beta 6$ -positive sEVs on endothelial cells, we utilised PC3 cells stably transfected with control shRNA (PC3-shCtrl), shRNA to  $\beta 6$  integrin subunit (PC3-sh $\beta 6$ ) or shRNA to  $\beta 5$  integrin subunit (PC3-sh $\beta 5$ ) and C4-2B PrCa cells transfected with either empty vector (C4-2B-Mock) or  $\beta 6$  cDNA-expression vector (C4-2B- $\alpha\text{v}\beta 6$ ). We isolated sEVs from PC3-shCtrl, -sh $\beta 6$  and -sh $\beta 5$  cells through high-speed differential ultracentrifugation (100,000 g) and further removed contaminants by iodixanol density gradient centrifugation. The sEV fractions corresponding to a density of 1.12 g/mL were characterised for size distribution by NTA. The majority of the PC3-shCtrl sEVs, -sh $\beta 6$  sEVs and -sh $\beta 5$  sEVs are < 150 nm in size (Figure 3a). The average yield of sEVs from PC3 cells is  $\sim 2.5 \times 10^3$  sEVs/cell/48 h. Furthermore, NTA data from C4-2B-Mock sEVs and - $\alpha\text{v}\beta 6$  sEVs also show that the majority of the sEVs exhibit a particle size of < 150 nm (Figure 3b).



**Figure 2.** Transfer of prostate cancer cell-derived  $\alpha v\beta 6$ -positive sEVs to microvascular and aortic endothelial cells.

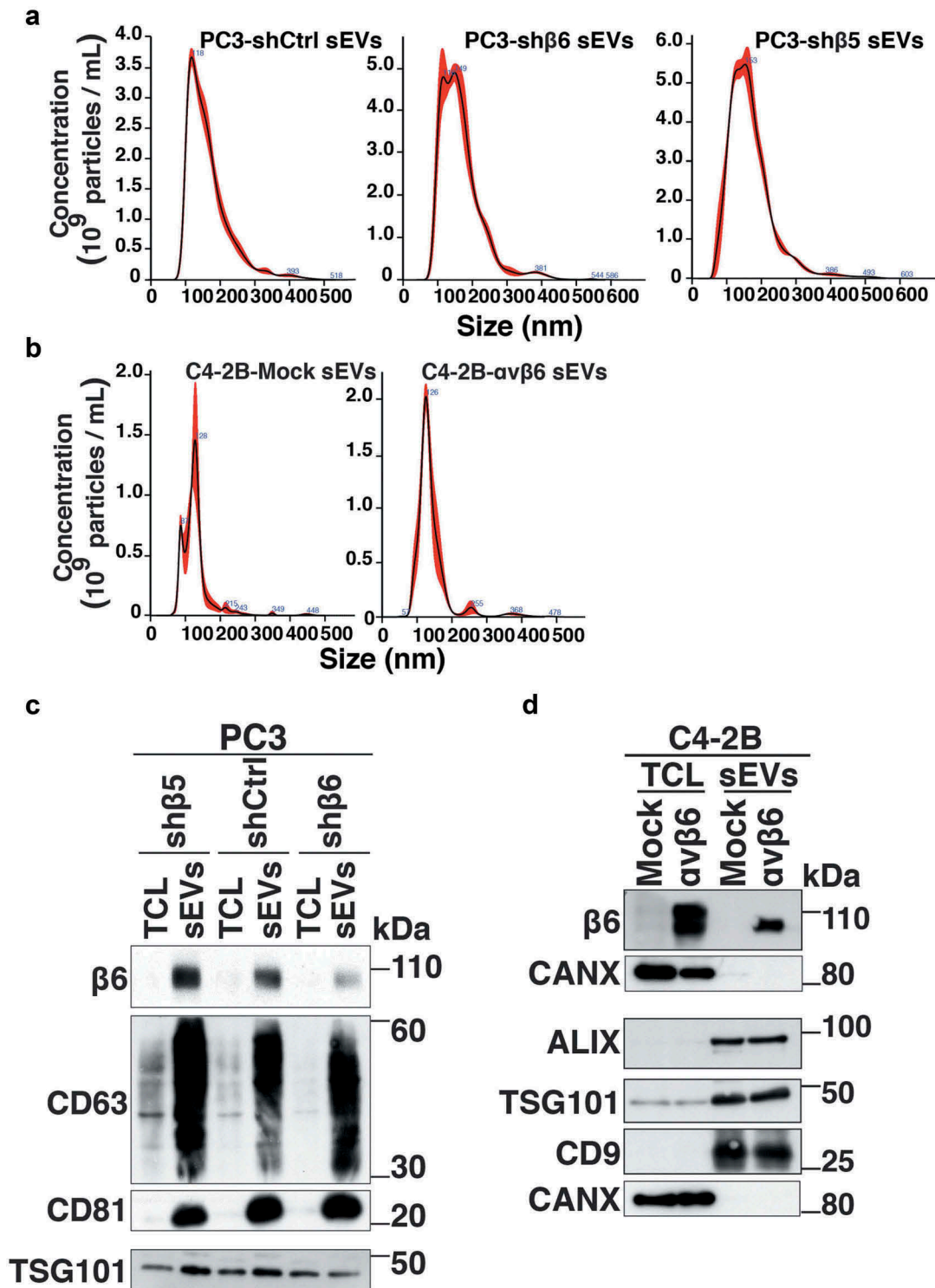
(a) Nanoparticle tracking analysis (NTA) of PC3 sEVs. (b) Left panel, IB analysis for expression of  $\beta 6$  integrin subunit, CD63, CD81 and CANX (non-reducing conditions) in TCL and sEV lysates from PC3 cells; right panel, expression of ALIX and TSG101 (reducing conditions) in TCL and sEV lysates from PC3 cells. (c) Quantification of  $\beta 6$  mRNA expression by q-PCR in PC3 cells (positive control for  $\beta 6$  mRNA expression) and BAEC treated with  $\alpha v\beta 6$ -positive PC3 sEVs for 4, 8 and 16 h or PBS vehicle control for 16 h. The GAPDH levels were comparable in PC3 and BAEC. The  $\beta 6$  mRNA expression is normalised to GAPDH. (d) Quantification of  $\beta 6$  mRNA expression by q-PCR in PC3 cells and HMEC1 treated with  $\alpha v\beta 6$ -positive PC3 sEVs for 2, 4, 8, 16 and 24 h or PBS vehicle control for 24 h. The GAPDH levels were comparable in PC3 and HMEC1. The  $\beta 6$  mRNA expression is normalised to GAPDH. (e) HMEC1 plated ( $2 \times 10^5$ ) in six-well plates were incubated with PBS or PC3 sEVs for the indicated time lengths (6 and 24 h) followed by IB analysis of TCL under non-reducing conditions for expression of  $\beta 6$  and CANX (loading control). (f) HMEC1 plated ( $2 \times 10^5$ ) in six-well plates were incubated with PBS, or iodixanol density gradient separated PC3 sEVs for indicated time lengths (6, 16 and 24 h) followed by IB analysis for expression of  $\beta 6$  integrin subunit and CANX (loading control) in TCL under non-reducing conditions. (g) FACS analysis of cell-surface expression of  $\alpha v\beta 6$  integrin on HMEC1 incubated with PBS or PC3 sEVs for 18 h. The shift in fluorescence intensity for positive control PC3 cells (red line) or HMEC1 incubated with PC3 sEVs (blue line) show cell-surface expression of  $\alpha v\beta 6$  integrin compared to the isotype control (green line) and HMEC1 incubated with PBS-only (orange line). Different gels were used to separate samples under reducing or non-reducing conditions.

The average yield of sEVs from C4-2B cells is  $\sim 1.5 \times 10^3$  sEVs/cell/48 h. IB analysis of the TCL and the sEVs from PC3-sh $\beta 5$ , -shCtrl and -sh $\beta 6$  cells shows similar levels of  $\beta 6$  integrin subunit in -sh $\beta 5$  sEVs and -shCtrl sEVs whereas its expression is significantly reduced in the sEVs from -sh $\beta 6$  cells (Figure 3c). Expression of sEV markers (CD63, CD81 and TSG101) is enriched for sEVs in comparison to respective TCL (Figure 3c). IB analysis of TCL and sEVs from C4-2B-Mock and - $\alpha v\beta 6$  cells shows the expression of  $\beta 6$  only in the TCL and sEVs from C4-2B- $\alpha v\beta 6$  cells. Expression of sEV markers (ALIX, TSG101 and CD9) is enriched for both C4-2B-Mock sEVs and - $\alpha v\beta 6$  sEVs in comparison to

their respective TCL (Figure 3d). Overall, our data show that the  $\alpha v\beta 6$  integrin does not alter expression of sEV-specific markers in sEVs.

### ***$\alpha v\beta 6$ integrin in prostate cancer sEVs increases motility and tube forming potential of endothelial cells***

Increased proliferation, motility and tube formation by endothelial cells are considered to be hallmarks of angiogenesis [43]. To test the impact of  $\alpha v\beta 6$ -positive sEVs on HMEC1 viability, we incubated HMEC1 with PBS or sEVs from PC3-shCtrl, -sh $\beta 6$ , -sh $\beta 5$  (data not



**Figure 3.** Characterisation of prostate cancer cell-derived sEVs upon knockdown or expression of  $\beta 6$  integrin subunit in prostate cancer cells. (a) NTA of the sEV fraction (density 1.12 g/mL) from the iodixanol density gradient of PC3-shCtrl, PC3-sh $\beta 6$  and PC3-sh $\beta 5$  cell-derived sEVs. (b) NTA analysis of C4-2B-Mock or C4-2B- $\alpha\beta 6$ -derived sEVs. (c) IB analysis for expression of  $\beta 6$  integrin subunit, CD63, CD81, (non-reducing conditions) and TSG101 (reducing conditions) in TCL and sEV lysates from PC3-sh $\beta 5$ , -shCtrl and -sh $\beta 6$  cells. (d) IB analysis for expression of  $\beta 6$  integrin subunit, CANX (non-reducing conditions) and ALIX, TSG101, CD9 and CANX (reducing conditions) in TCL and sEV lysates from C4-2B-Mock or - $\alpha\beta 6$  cells. Different gels were used to separate samples under reducing or non-reducing conditions.

shown) and C4-2B-Mock, - $\alpha\beta 6$  cells and performed trypan blue dye exclusion assays (Fig. S2). Our analysis shows that relative to incubation with PBS, there is no

significant change in the viability of HMEC1 upon incubation with respective sEVs (Fig. S2). We also investigated the impact of  $\beta 6$  or  $\beta 5$  integrin subunit

knockdown on the viability of PrCa cells. Our analysis shows that there is no significant change in the viability of PC3-sh $\beta$ 6 or PC3-sh $\beta$ 5 cells compared to PC3-shCtrl cells (data not shown).

To further evaluate the role of  $\alpha$  $\beta$ 6-positive sEVs on the motility of HMEC1, we performed Boyden chamber assays. In comparison to incubation with PBS, there is a significant increase ( $P < 0.05$ ) in the motility of HMEC1 upon incubation with PC3-shCtrl sEVs (Fig. S3A). Compared to incubation with PC3-shCtrl sEVs, motility of HMEC1 is significantly decreased ( $P < 0.0005$ ) upon incubation with PC3-sh $\beta$ 6 sEVs (Fig. S3A) and not significantly altered upon incubation with PC3-sh $\beta$ 5 sEVs (Fig. S3A). Furthermore, there is a significant increase in motility of HMEC1 upon incubation with C4-2B- $\alpha$  $\beta$ 6 sEVs compared to both incubation with PBS ( $P < 0.005$ ) or C4-2B-Mock sEVs ( $P < 0.05$ ) (Fig. S3B). Finally, we investigated the impact of PC3 sEVs on the motility of HMEC1 in the absence of chemotaxis. We demonstrate that even in the absence of chemotaxis, there is a significant increase in motility of HMEC1 upon incubation with PC3 sEVs compared to incubation with PBS ( $P < 0.005$ ) (Fig. S3C). Overall, the results from our study show that  $\alpha$  $\beta$ 6-positive sEVs significantly increase the motility of HMEC1.

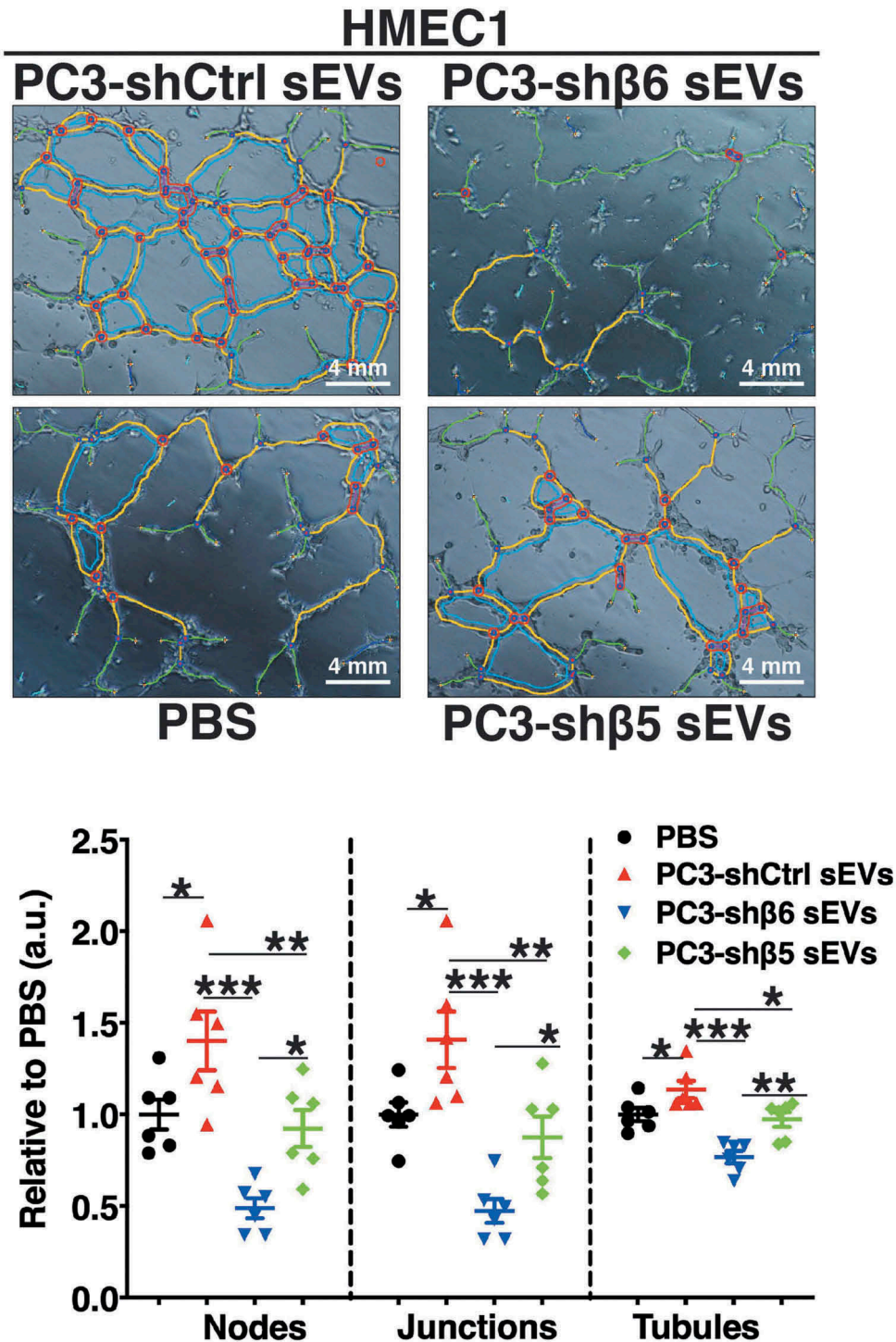
Angiogenesis is known to be a vital process associated with PrCa progression [2]; however, the key molecular mechanisms that regulate PrCa cell-mediated angiogenesis have been elusive. Owing to the significant impact that  $\alpha$  $\beta$ 6-positive sEVs have on the motility of microvascular endothelial cells, we further evaluated the implications of  $\alpha$  $\beta$ 6-positive sEVs on tube forming potential of endothelial cells. We performed tube formation assays which provided a rapid and quantitative method for assessing the angiogenic potential of HMEC1 and BAEC plated on Matrigel and incubated with PBS or sEVs from PC3-shCtrl, -sh $\beta$ 6, -sh $\beta$ 5 and C4-2B-Mock, - $\alpha$  $\beta$ 6 cells. The phase-contrast microscopy images from these tube formation assays show extensive branching and tube formation of HMEC1 upon incubation with PC3-shCtrl sEVs (Figure 4, upper panel) compared to incubation with the PBS-only control. On the other hand, branching and tube formation is abrogated upon incubation with PC3-sh $\beta$ 6 sEVs (Figure 4, upper panel) and mildly reduced upon incubation with PC3-sh $\beta$ 5 sEVs (Figure 4, upper panel). The phase-contrast microscopy images were further quantified for the number of nodes, junctions and tubules formed in each sEV incubation group. Compared to incubation with PBS, there is a significant increase in the number of nodes ( $P < 0.05$ ), junctions ( $P < 0.05$ ) and tubules ( $P < 0.05$ ) formed upon incubation with PC3-shCtrl sEVs (Figure 4, lower panel). Compared to incubation with PC3-shCtrl sEVs, there is a

highly significant reduction in the number of nodes ( $P < 0.0005$ ), junctions ( $P < 0.0005$ ) and tubules ( $P < 0.0005$ ) formed upon incubation with PC3-sh $\beta$ 6 sEVs (Figure 4, lower panel). In comparison to incubation with PBS, there is no impact of PC3-sh $\beta$ 5 sEVs on formation of nodes, junctions and tubules (Figure 4, lower panel). A significant reduction in the number of nodes ( $P < 0.005$ ), junctions ( $P < 0.005$ ) and tubules ( $P < 0.05$ ) formed by HMEC1 is observed upon incubation with PC3-sh $\beta$ 5 sEVs compared to incubation with PC3-shCtrl sEVs (Figure 4, lower panel). A significant decrease in formation of nodes ( $P < 0.05$ ), junctions ( $P < 0.05$ ) and tubules ( $P < 0.005$ ) formed by HMEC1 is observed upon incubation with PC3-sh $\beta$ 6 sEVs compared to incubation with PC3-sh $\beta$ 5 sEVs (Figure 4, lower panel). Furthermore, the phase-contrast microscopy images show extensive branching and tube formation of HMEC1 upon incubation with C4-2B- $\alpha$  $\beta$ 6 sEVs compared to incubation with PBS controls (Figure 5a, upper panel). The quantification of phase-contrast microscopy images for number of nodes, junctions and tubules formed in each incubation group also shows that there is a highly significant increase in nodes ( $P < 0.0005$ ), junctions ( $P < 0.0005$ ) and tubules ( $P < 0.005$ ) formation by HMEC1 upon incubation with C4-2B- $\alpha$  $\beta$ 6 sEVs compared to incubation with PBS (Figure 5a, lower panel). In comparison to incubation with C4-2B-Mock sEVs, there is a significant increase in nodes ( $P < 0.005$ ), junctions ( $P < 0.05$ ) and tubules ( $P < 0.05$ ) formation by HMEC1 upon incubation with C4-2B- $\alpha$  $\beta$ 6 sEVs (Figure 5a, lower panel).

To test whether the impact of  $\alpha$  $\beta$ 6-positive sEVs is not limited only to microvascular endothelial cells, we included another endothelial cell type, bovine aortic endothelial cells (BAEC). Compared to incubation with PBS, there is a significant increase in nodes ( $P < 0.005$ ), junctions ( $P < 0.05$ ) and tubules ( $P < 0.005$ ) formed by BAEC upon incubation with C4-2B- $\alpha$  $\beta$ 6 sEVs (Figure 5b). In addition, compared to incubation with C4-2B-Mock sEVs, there is a significant increase in nodes ( $P < 0.005$ ), junctions ( $P < 0.005$ ) and tubules ( $P < 0.05$ ) formed by BAEC upon incubation with C4-2B- $\alpha$  $\beta$ 6 sEVs (Figure 5b). Overall, the results from our study show that  $\alpha$  $\beta$ 6-positive sEVs support the tube formation capability of endothelial cells.

### ***Uptake of prostate cancer cell-derived $\alpha$ $\beta$ 6-positive sEVs regulate angiogenic signalling in microvascular endothelial cells***

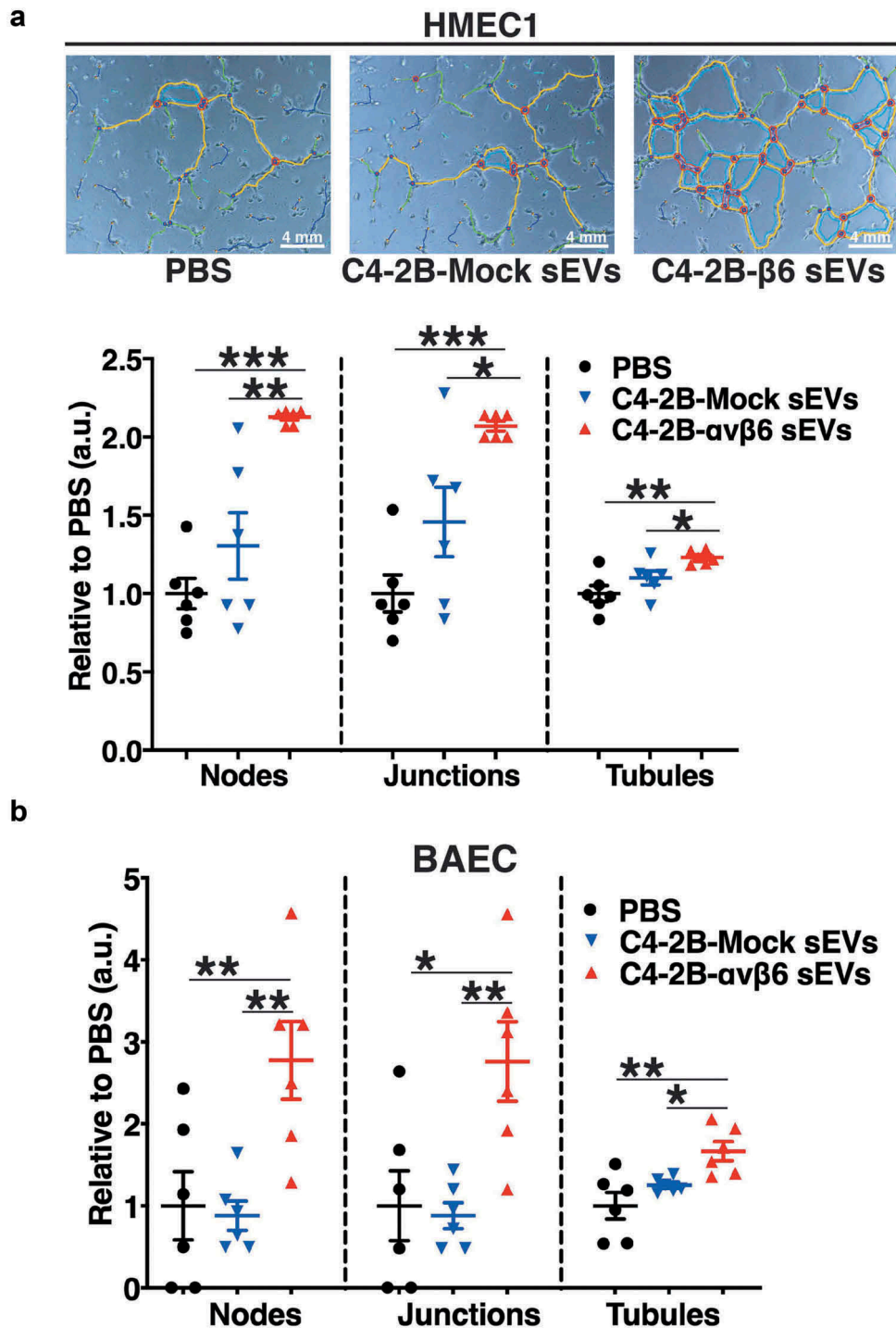
We have previously demonstrated that the  $\alpha$  $\beta$ 6 integrin negatively regulates protein levels of the signalling molecule STAT1 both in PC3 cells and in the sEVs derived from them [19]. Since elevated STAT1 is



**Figure 4.** Down-regulation of  $\alpha v\beta 6$  integrin in prostate cancer sEVs modulates the angiogenic potential of microvascular endothelial cells. HMEC1 were seeded ( $1.5 \times 10^4$ , replicates  $n = 3$ ) on 96-well plates coated with Matrigel and incubated with PBS or iodixanol density gradient separated sEVs ( $0.3 \times 10^9$  vesicles) from PC3-shCtrl, -shβ6 or -shβ5 cells. The upper panel shows representative micrographs ( $n = 6$  different fields for each group) of tubes formed during tube formation assays on HMEC1 after 5 h incubation with respective sEV type. The lower panel shows dot plots representing the number of nodes, junctions and tubules formed by HMEC1 in each sEV incubation group relative to PBS ( $n = 6$  different fields for each group). Values are reported as mean  $\pm$  SEM,  $*P < 0.05$ ;  $**P < 0.005$ ;  $***P < 0.0005$  determined by one-way ANOVA with post hoc Fisher's LSD test.

known to be a negative regulator of angiogenesis [44,45], we hypothesised that the transfer of  $\alpha v\beta 6$ -positive sEVs to HMEC1 might negatively regulate

expression and activation of STAT1 protein in HMEC1. To test this hypothesis, we utilised PrCa cells harbouring CRISPR/Cas9-mediated down-



**Figure 5.** Expression of  $\alpha$ v $\beta$ 6 integrin in prostate cancer sEVs modulates the tube forming potential of endothelial cells.

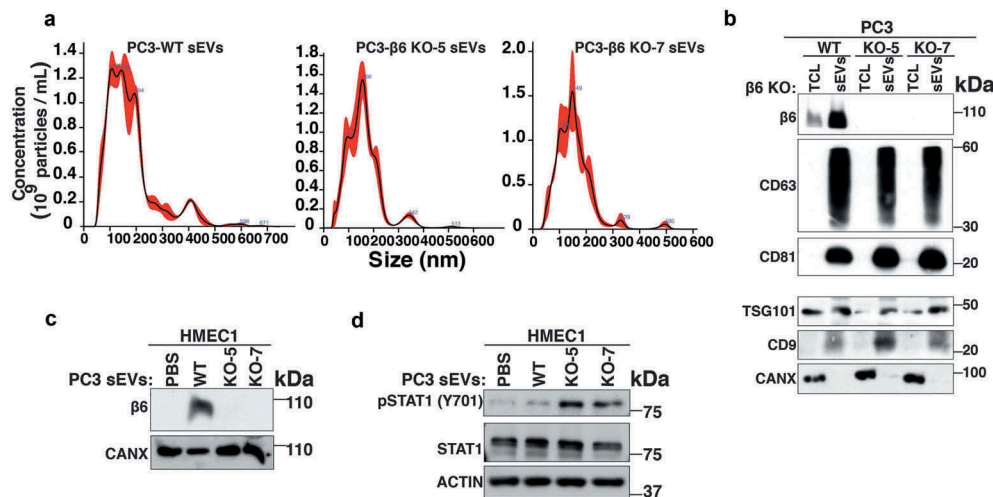
(a) HMEC1 were seeded ( $1.5 \times 10^4$ , replicates  $n = 3$ ) on 96-well plates coated with Matrigel and incubated with PBS or iodixanol density gradient separated sEVs ( $0.3 \times 10^9$  vesicles) from C4-2B-Mock or - $\alpha$ v $\beta$ 6 cells. The upper panel shows representative micrographs ( $n = 6$  different fields for each group) of tubes formed by HMEC1 after 5 h incubation with respective sEV type. The lower panel shows dot plots representing the number of nodes, junctions and tubules formed by HMEC1 in each sEV incubation group relative to PBS ( $n = 6$  different fields for each group). (b) BAEC were seeded ( $1.5 \times 10^4$ , replicates  $n = 3$ ) on 96-well plates coated with Matrigel and incubated with PBS or iodixanol density gradient separated sEVs ( $0.3 \times 10^9$  vesicles) from C4-2B-Mock or - $\alpha$ v $\beta$ 6 cells. Dot plots represent the number of nodes, junctions and tubules formed by BAEC 8 h after incubation with each sEV group relative to PBS ( $n = 6$  different fields for each group). Values are reported as mean  $\pm$  SEM, \* $P < 0.05$ ; \*\* $P < 0.005$ ; \*\*\* $P < 0.0005$  determined by one-way ANOVA with post hoc Fisher's LSD test.

regulation of  $\beta 6$  integrin subunit (PC3- $\beta 6$  KO-5 and PC3- $\beta 6$  KO-7) or CRISPR/Cas9 construct transfected cells that endogenously express  $\beta 6$  integrin subunit (PC3-WT). We isolated sEVs from PC3-WT, - $\beta 6$  KO-5 and - $\beta 6$  KO-7 cells through high-speed differential ultracentrifugation (100,000 g) and characterised them for size distribution by NTA. The majority of PC3-WT, - $\beta 6$  KO-5 and - $\beta 6$  KO-7 sEVs are < 150 nm in size (Figure 6a). IB analysis of the sEVs and respective TCL from PC3-WT, - $\beta 6$  KO-5 and - $\beta 6$  KO-7 cells shows expression of  $\beta 6$  integrin subunit only in TCL and sEVs from PC3-WT cells (Figure 6b). CANX is used as the loading control for TCL and known to be absent in sEVs (Figure 6b). As expected, the levels of CD63, CD81, CD9 and TSG101 are highly enriched in the sEV preparations as compared to TCL (Figure 6b). The absence of CANX in the sEV preparations confirms the removal of contaminants in our isolated sEVs (Figure 6b). Upon incubation with sEVs from  $\alpha v\beta 6$  integrin expressing cells (PC3-WT), by IB analysis we demonstrate the efficient uptake of  $\beta 6$  in HMEC1, while  $\beta 6$  is not present in HMEC1 incubated with sEVs derived from  $\beta 6$ -negative cells (PC3- $\beta 6$  KO-5 and PC3- $\beta 6$  KO-7) (Figure 6c). Further evaluation of  $\alpha v\beta 6$ -positive sEV-mediated impact on HMEC1 signalling shows that incubation of HMEC1 with sEVs from PC3- $\beta 6$  KO-5 or - $\beta 6$  KO-7 cells results in increased expression of pSTAT1(Y701) in comparison with

HMEC1 incubated with sEVs from PC3-WT cells or PBS (Figure 6d).

We further corroborated our findings with PC3-shCtrl, -sh $\beta 6$  and -sh $\beta 5$  sEVs by testing their impact on angiogenic pathways in recipient HMEC1. Incubation of HMEC1 with PC3-sh $\beta 6$  sEVs results in the up-regulation of pSTAT1 (Y701) levels compared to incubation with PBS or PC3-shCtrl and -sh $\beta 5$  sEVs (Figure 7a). Similar to the results with PC3 sEVs, incubation of HMEC1 with C4-2B- $\alpha v\beta 6$  sEVs results in lower pSTAT1(Y701) levels compared to incubation with PBS or C4-2B-Mock sEVs (Fig. S4).

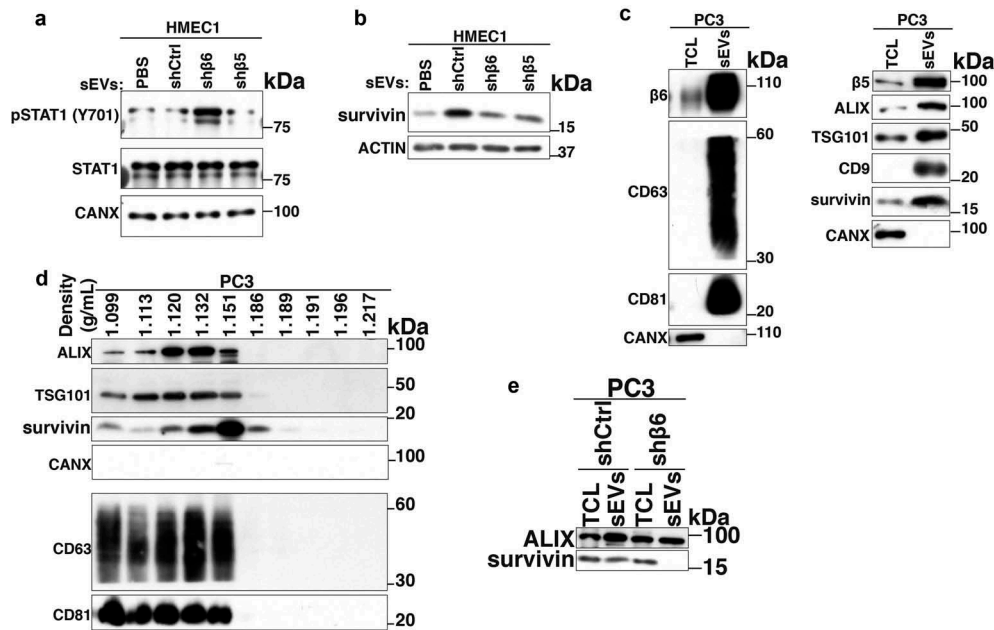
Since  $\alpha v\beta 6$  integrin is known to regulate survivin expression in PrCa cells [34] and survivin is known to promote angiogenesis [46–48], we also investigated changes in the levels of survivin in HMEC1 upon incubation with  $\alpha v\beta 6$ -positive sEVs. Our data demonstrate that the expression of survivin protein is reduced in HMEC1 upon incubation with PC3-sh $\beta 6$  sEVs compared to incubation with PC3-shCtrl sEVs (Figure 7b). This led us to investigate whether the BIRC5 (survivin) mRNA expression is altered in HMEC1 upon treatment with PC3 sEVs. The qPCR data show no significant differences in survivin mRNA levels in HMEC1 upon incubation with sEVs from PC3-shCtrl, -sh $\beta 5$  or -sh $\beta 6$  (data not shown). We also characterised PC3 sEVs for expression of survivin by IB. In IB, the sEVs from PC3 cells show enrichment of survivin,  $\beta 5$  integrin subunit (Figure 7c, right panel) along with  $\beta 6$  integrin subunit, sEV markers CD63, CD81 (Figure 7c,



**Figure 6.** Transfer of  $\alpha v\beta 6$ -positive sEVs derived from CRISPR/Cas9 genetically modified prostate cancer cells to microvascular endothelial cells regulates STAT1 signalling.

(a) NTA of PC3-WT, PC3- $\beta 6$  KO-5 and PC3- $\beta 6$  KO-7 cell-derived sEVs. (b) IB analysis for expression of  $\beta 6$  integrin subunit, CD63, CD81 (non-reducing conditions), TSG101, CD9 and CANX (reducing conditions) in TCL and sEV lysates from PC3-WT, PC3- $\beta 6$  KO-5 or PC3- $\beta 6$  KO-7 cells harbouring CRISPR/Cas9-mediated down-regulation of  $\beta 6$  integrin subunit. (c) HMEC1 were plated ( $2 \times 10^5$ ) in six-well plates and incubated with sEVs derived from PC3-WT, PC3- $\beta 6$  KO-5 or PC3- $\beta 6$  KO-7 cells for 18 h and after incubation, the TCL were analysed by IB under non-reducing conditions for expression of  $\beta 6$  integrin subunit and CANX (loading control). (d) HMEC1 plated ( $2 \times 10^5$ ) in six-well plates were incubated with sEVs derived from PC3-WT, PC3- $\beta 6$  KO-5 or PC3- $\beta 6$  KO-7 for 18 h and after incubation, the TCL were analysed by IB under reducing conditions for expression of pSTAT1(Y701), STAT1 and ACTIN (loading control). Different gels were used to separate samples under reducing or non-reducing conditions





**Figure 7.** Transfer of prostate cancer cell-derived  $\alpha\beta 6$ -positive sEVs to microvascular endothelial cells regulates survivin levels.

(a) HMEC1 were plated ( $2 \times 10^5$ ) in six-well plates and incubated with PBS or sEVs derived from PC3-shCtrl, -sh $\beta 6$  or -sh $\beta 5$  cells for 18 h and after incubation, the TCL were analysed by IB under reducing conditions for expression of pSTAT1(Y701), STAT1 and ACTIN (loading control). (b) HMEC1 were plated ( $2 \times 10^5$ ) in six-well plates and incubated with PBS or sEVs derived from PC3-shCtrl, -sh $\beta 6$  or -sh $\beta 5$  cells for 18 h and after incubation, the TCL were analysed by IB under reducing conditions for expression of survivin and ACTIN (loading control). (c) Left panel, IB analysis for expression of  $\beta 6$  integrin subunit, CD63, CD81 and CANX (non-reducing conditions); right panel, IB analysis for expression of  $\beta 5$  integrin subunit, ALIX, TSG101, CD9, survivin and CANX (reducing conditions) in TCL and sEV lysates from PC3 cells. (d) Iodixanol density gradient analysis of PC3 sEVs was performed as described in the Materials and methods. Expression of ALIX, TSG101, survivin, CANX (reducing conditions), CD63 and CD81 (non-reducing conditions) analysed by IB of 10 consecutive iodixanol density gradient fractions is shown. (e) IB analysis for expression of ALIX and survivin (reducing conditions) in TCL and sEV lysates from PC3-shCtrl and -sh $\beta 6$  cells. Different gels were used to separate samples under reducing or non-reducing conditions.

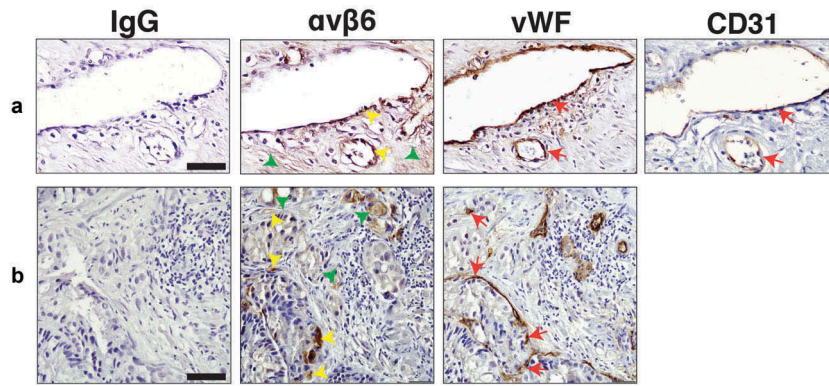
left panel), ALIX, TSG101 and CD9 (Figure 7c, right panel) compared to TCL (Figure 7c). sEVs did not express CANX (Figure 7c). We also observe the expression of survivin along with sEV markers (ALIX, TSG101, CD9, CD63 and CD81) in iodixanol density gradient fractions from PC3-derived sEV samples (Figure 7d). The ER marker CANX known to be absent in sEVs is not expressed in any of the 10 fractions (Figure 7d). Interestingly, the expression of survivin remains unaltered in PC3-sh $\beta 6$  TCL compared to PC3-shCtrl TCL, whereas it is significantly reduced in sEVs from PC3-sh $\beta 6$  cells compared to sEVs from PC3-shCtrl cells (Figure 7e).

These findings suggest that incubation of HMEC1 with PrCa cell-derived sEVs harbouring down-regulation of  $\beta 6$  integrin subunit and associated cargo may increase STAT1 signalling or decrease survivin expression to modulate the angiogenic potential of HMEC1.

#### ***$\alpha\beta 6$ integrin is expressed in blood vessels found in prostate cancer patient tissues***

Based on our observation that  $\alpha\beta 6$  integrin is transferred via PC3 sEVs to endothelial cells, we hypothesised that

$\alpha\beta 6$  integrin might be expressed in blood vessels in human PrCa tissue specimens. To test this hypothesis, we performed IHC on serial sections from PrCa tissue specimens to evaluate the expression of  $\alpha\beta 6$  integrin in blood vessels. The  $\alpha\beta 6$  integrin is expressed in the epithelial compartment in 11 of 16 PrCa cases evaluated. Among the  $\alpha\beta 6$  integrin-positive PrCa cases, the  $\alpha\beta 6$  integrin is expressed in up to 75% of PrCa cells (3+ intensity). vWF or CD31, a marker of blood vessels, is expressed (3+ intensity) in blood vessels. Using vWF and CD31, we show that in three of 16 PrCa cases,  $\alpha\beta 6$  integrin is detected in endothelial cells (Figure 8). All these three cases have a Gleason score 10 diagnosis. The cases diagnosed as Gleason scores 7, 8, 9 do not show expression of  $\alpha\beta 6$  integrin in blood vessels. In 5 of 16 PrCa cases, both epithelial and endothelial cells are negative for expression of  $\alpha\beta 6$  integrin (Fig. S5A). In 8 of 16 PrCa cases,  $\alpha\beta 6$  integrin is expressed only in epithelial cells but not in endothelial cells (Fig. S5B). In conclusion, this finding that the  $\alpha\beta 6$  integrin is in endothelial cells in PrCa patient samples is novel since  $\alpha\beta 6$  integrin was previously known to be either expressed by cells of epithelial origin during conditions of injury, wound



**Figure 8.** Expression of  $\alpha v\beta 6$  integrin, vWF and CD31 in blood vessels of human prostate cancer tissues.

Serial sections of human PrCa tissues were analysed for IgG (isotype control),  $\alpha v\beta 6$  integrin, vWF or CD31 expression by immunohistochemistry (IHC). Representative images of IgG (first panel),  $\alpha v\beta 6$  integrin (second panel), vWF (third panel) and CD31 (fourth panel) expression from one (CD31) or two different PrCa cases (a, b) are shown. Green arrowheads highlight the cancer cells that show expression of  $\alpha v\beta 6$  integrin, yellow arrowheads highlight the endothelial cells that show expression of  $\alpha v\beta 6$  integrin and red arrows highlight the endothelial cells that show expression of vWF or CD31 in blood vessels in serial sections. Scale bar, 100  $\mu\text{m}$  (a); 200  $\mu\text{m}$  (b).

healing and cancer [49,50] or *de novo* induced in endothelial cells under conditions of infection and injury [22–24].

## Discussion

This is the first study that explores the functional impact of PrCa cell-derived sEVs that express  $\alpha v\beta 6$  integrin ( $\alpha v\beta 6$ -positive sEVs) on endothelial cells in the TME. The present study demonstrates for the first time that the  $\alpha v\beta 6$  integrin protein is transferred by  $\alpha v\beta 6$ -positive sEVs to endothelial cells and is functionally active in the recipient endothelial cells. Furthermore, this study also demonstrates that the  $\alpha v\beta 6$ -positive sEVs promote microvascular endothelial cell motility and significantly increase tube formation of endothelial cells. Overall, the  $\alpha v\beta 6$ -positive sEVs impact mechanistically endothelial cell functions.

We show for the first time that the  $\alpha v\beta 6$  integrin is also expressed in PC3 LEVs; however, in this study, our focus is on sEVs since a prior proteomic analysis of PC3 sEVs had shown that several aberrations follow down-regulation of  $\alpha v\beta 6$  integrin and had indicated that these aberrant sEVs might influence endothelial cell behaviour [19].

*De novo* induction of  $\alpha v\beta 6$  integrin expression in endothelial cells under conditions of infection and injury has been reported [22–24]. In human dermal microvascular endothelial cells and in tumour-associated endothelial cells purified from human breast carcinomas (B-TEC), oxytocin induces  $\alpha v\beta 6$  integrin expression [22]. Among other examples, exposure to lipopolysaccharide (LPS) enhances expression of  $\alpha v\beta 6$

integrin in a toll like receptor 4 (TLR)4-dependent manner in cardiac endothelial cells (CEC) [23]. Similarly, cytomegalovirus (CMV) infection induces  $\alpha v\beta 6$  integrin expression in both epithelial and endothelial cells of pulmonary, uterine and placental blood vessels at the sites of CMV infection-mediated injury [24]. Furthermore,  $\alpha v\beta 6$  integrin expressed on small vascular tufts during later stages of a healing skin wound has been assumed to impact remodelling of the vasculature [51]. In view of these previous studies, and on the fact that sEVs are known to carry mRNA as their cargo, we investigated the possibility of PrCa cell-derived  $\alpha v\beta 6$ -sEVs-mediated  $\beta 6$  mRNA transfer or induction in HMEC1. We do not detect an increase of  $\beta 6$  mRNA in endothelial cells upon incubation with  $\alpha v\beta 6$ -positive sEVs (Figure 2c,d), suggesting that  $\beta 6$  mRNA is neither transferred nor induced in endothelial cells. This finding also excludes the possibility that cytokines or growth factors in  $\alpha v\beta 6$ -positive sEVs could be responsible for the induction of  $\beta 6$  integrin in endothelial cells.

Tumour angiogenesis involves multiple cellular processes, including endothelial cell proliferation, migration, extracellular matrix reorganisation and tube formation [43]. It is known that inactivation of the gene encoding for the  $\beta 6$  integrin subunit results in reduced keratinocyte migration [52]. The  $\alpha v\beta 6$  integrin transferred by sEVs could be crucial for the adhesion and migration of PrCa cells [17]. Similar to these previous studies, results from our motility assays suggest that  $\alpha v\beta 6$  and/or  $\alpha v\beta 6$ -regulated cargo in  $\alpha v\beta 6$ -positive sEVs drives migration of microvascular endothelial cells. Here, using *in vitro* tube formation assays that

mimic angiogenesis [53], we present strong evidence that sEVs, derived from PrCa cells with down-regulated  $\beta 6$  integrin subunit, cause a highly significant reduction of capillary-like tube formation by endothelial cells (Figs. 4 & 5). In contrast, incubation of endothelial cells with sEVs from PC3 cells transfected with shRNA to another  $\alpha v$ -binding subunit,  $\beta 5$ , only slightly reduces tube formation, possibly by using the  $\alpha v\beta 6$  integrin that remains expressed in PC3-sh $\beta 5$  sEVs.

We have demonstrated that siRNA-mediated down-regulation of  $\beta 6$  integrin subunit in PrCa cells results in increased STAT1 protein levels both in cells and sEVs derived from them [19]. STAT1 may act as a tumour suppressor in PrCa [19,54] and has been shown to be a negative regulator of angiogenesis [44,45]. We observe that uptake of  $\alpha v\beta 6$ -positive sEVs led to down-regulation of pSTAT1(Y701) levels in microvascular endothelial cells (Figs. 6d & 7a). However, the total STAT1 levels remain unchanged in microvascular endothelial cells; we, therefore, propose a novel pathway that differed from the pathway identified in PrCa cells and their sEVs via our proteomic data [19]. The findings from this study are suggestive of different  $\alpha v\beta 6$ -mediated regulatory mechanisms of STAT1 signalling in cancer cells versus microvascular endothelial cells. With respect to these STAT1 findings, the  $\alpha v\beta 6$  integrin is also known to be a major activator of TGF- $\beta 1$  [24,55–57]. Also, the  $\alpha v\beta 6$  integrin interacts with TGF $\beta$  receptor II (T $\beta$ RII) through the  $\beta 6$  cytoplasmic domain [39]. TGF- $\beta 1$  plays a critical role in tumour angiogenesis [58–60] and the antagonistic effect of TGF- $\beta 1$  on STAT1 signalling has previously been shown [61]. Therefore, we speculate that upon transfer from PrCa cell-derived sEVs to microvascular endothelial cells,  $\alpha v\beta 6$  integrin activates TGF- $\beta 1$  leading to inhibition of STAT1 signalling and thus increased angiogenesis.

We have previously demonstrated that expression of  $\alpha v\beta 6$  integrin in C4-2B and LNCaP PrCa cells results in an androgen receptor-mediated increased expression of survivin [34]. We found that survivin is expressed in PC3 sEVs and its levels are significantly reduced in PC3-sh $\beta 6$  sEVs; however, survivin levels are unaltered in PC3-sh $\beta 6$  cells compared to PC3-shCtrl cells. This discrepancy of  $\alpha v\beta 6$  integrin not regulating survivin in PC3 cells might be attributed to the absence of androgen receptor in these cells. Survivin has been detected in sEVs derived from plasma of PrCa patients [62] and is known to be a critical mediator of angiogenesis [46–48]. This led us to hypothesise that the uptake of  $\alpha v\beta 6$ -positive sEVs by microvascular endothelial cells may increase survivin levels in endothelial cells. We observe that mRNA levels of survivin are unaltered in

microvascular endothelial cells upon incubation with  $\alpha v\beta 6$ -positive sEVs, whereas survivin protein levels are increased. We conclude that survivin protein is transferred via  $\alpha v\beta 6$ -positive sEVs to microvascular endothelial cells. We speculate that the lack of  $\alpha v\beta 6$  integrin in PC3 cells may inhibit the sorting of survivin in sEVs; this may result in a reduced transfer of survivin via PC3-sh $\beta 6$  sEVs to microvascular endothelial cells. Furthermore, the antagonistic effect between STAT1 and survivin shown in gastric cancer cells and tissues [63] supports our evidence of an angiogenic signalling pathway mediated by the uptake of  $\alpha v\beta 6$ -positive sEVs in microvascular endothelial cells.

In summary, our study demonstrates that by transferring  $\alpha v\beta 6$  integrin and/or potential angiogenic cargoes via sEVs from  $\alpha v\beta 6$ -positive PrCa cells to recipient endothelial cells, angiogenic programmes are potentially modulated in the recipient cells.

## Acknowledgments

We would like to thank Dr. Eric B. Kmiec and Dr. Pawel A. Bialk from the Gene Editing Institute, Christiana Health Care System, for generating the cell lines with CRISPR/Cas9-mediated  $\beta 6$  integrin subunit down-regulation; Dr. Joseph A. Madri, Department of Pathology, Yale University School of Medicine, New Haven, CT, USA for BAEC; Dr. Michael Root at Thomas Jefferson University for refractometer; Dr. James Keen and Yolanda Covarrubias, Sidney Kimmel Cancer Center (SKCC) Bio-imaging facility at Thomas Jefferson University for support with confocal imaging; Dr. Lei Yu and Amir Yarmahmoodi, SKCC Flow Cytometry facility at Thomas Jefferson University for technical support with NTA and FACS experiments; Dr. Zhijiu Zhong, Translational Research/Pathology facility at Thomas Jefferson University for technical support with immunohistochemistry experiments; Cancer Genomics & Bioinformatics Core facility, led by Dr. Paolo Fortina at Thomas Jefferson University for technical support with q-PCR experiments; Dr. Mark Fortini and Jennifer Wilson at Thomas Jefferson University for editing the manuscript; Veronica Robles for administrative assistance with the preparation of the manuscript.

## Author contributions

SRK and LRL conceptualised the study and designed experiments. SRK performed the experiments. IS generated Figure 1b and reviewed the manuscript. FQ assisted in performing an experiment and reviewed the manuscript. NN generated Figure 1a and reviewed the manuscript. EA assisted in performing an experiment and reviewed the manuscript. QL performed statistical analysis on data. SS and JK assisted in performing an experiment and reviewed the manuscript. PAM provided PrCa tissue sections, reviewed immunohistochemical staining and the manuscript. PHW and SV provided anti- $\alpha v\beta 6$  integrin Abs (6.2A1 and 6.4B4) and reviewed the manuscript. SRK, DCA and LRL analysed results and wrote the manuscript.

## Disclosure statement

No potential conflict of interest was reported by the author(s). Paul H. Weinreb is an employee and shareholder of Biogen. Shelia M. Violette is currently an employee of Admirx and, during this study, was an employee and shareholder of Biogen.

## Funding

This study was supported by NCI-P01-140043, R01-224769. This project is also funded, in part, under a Commonwealth University Research Enhancement Program grant with the Pennsylvania Department of Health (H.R.): SAP 4100072566; the Department specifically disclaims responsibility for any analyses, interpretations or conclusions. The research reported in this publication utilised the shared Flow Cytometry and Bio-imaging facilities at the SKCC and was supported by the National Cancer Institute of the National Institutes of Health under award number P30CA056036. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH; National Cancer Institute (US) [140043]; National Cancer Institute (US) [P30CA056036]; National Cancer Institute (US) [224769]; Pennsylvania Department of Health [SAP 4100072566].

## ORCID

Qin Liu  <http://orcid.org/0000-0001-9964-580X>

## References

- [1] Siegel RL, Miller KD, Jemal A. Cancer statistics, 2019. *C. A. Cancer J. Clin.* **2019**;69(1):7–34.
- [2] Hwang C, Heath EI. Angiogenesis inhibitors in the treatment of prostate cancer. *J Hematol Oncol.* **2010**;3:26.
- [3] Weidner N, Carroll PR, Flax J, et al. Tumor angiogenesis correlates with metastasis in invasive prostate carcinoma. *Am J Pathol.* **1993**;143(2):401–409.
- [4] Salem KZ, Moschetta M, Sacco A, et al. Exosomes in tumor angiogenesis. *Methods Mol Biol.* **2016**;1464:25–34.
- [5] Sato S, Vasaikar S, Eskaros A, et al. EPHB2 carried on small extracellular vesicles induces tumor angiogenesis via activation of ephrin reverse signaling. *JCI Insight.* **2019**;4:23.
- [6] Hoshino A, Costa-Silva B, Shen TL, et al. Tumour exosome integrins determine organotropic metastasis. *Nature.* **2015**;527(7578):329–335.
- [7] Kosaka N, Iguchi H, Hagiwara K, et al. Neutral sphingomyelinase 2 (nSMase2)-dependent exosomal transfer of angiogenic microRNAs regulate cancer cell metastasis. *J Biol Chem.* **2013**;288(15):10849–10859.
- [8] Ludwig N, Whiteside TL. Potential roles of tumor-derived exosomes in angiogenesis. *Expert Opin Ther Targets.* **2018**;22(5):409–417.
- [9] Thery C, Witwer KW, Aikawa E, 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. *J Extracell Vesicles.* **2018**;7(1):1535750.
- [10] Jimenez L, Yu H, McKenzie AJ, et al. Quantitative proteomic analysis of small and large extracellular vesicles (EVs) Reveals Enrichment of Adhesion Proteins in Small EVs. *J Proteome Res.* **2019**;18(3):947–959.
- [11] Kowal J, Arras G, Colombo M, et al. Proteomic comparison defines novel markers to characterize heterogeneous populations of extracellular vesicle subtypes. *Proc Natl Acad Sci U S A.* **2016**;113(8):E968–77.
- [12] Mathieu M, Martin-Jaular L, Lavieu G, et al. Specificities of secretion and uptake of exosomes and other extracellular vesicles for cell-to-cell communication. *Nat Cell Biol.* **2019**;21(1):9–17.
- [13] Bruno S, Chiabotto G, Favaro E, et al. Role of extracellular vesicles in stem cell biology. *Am J Physiol Cell Physiol.* **2019**;317(2):C303–C13.
- [14] Lasser C, Jang SC, Lotvall J. Subpopulations of extracellular vesicles and their therapeutic potential. *Mol Aspects Med.* **2018**;60:1–14.
- [15] Spinelli C, Adnani L, Choi D, et al. Extracellular vesicles as conduits of non-coding RNA emission and intercellular transfer in brain tumors. *Noncoding RNA.* **2018**;5:1.
- [16] DeRita RM, Sayeed A, Garcia V, et al. Tumor-derived extracellular vesicles require beta1 integrins to promote anchorage-independent growth. *iScience.* **2019**;14:199–209.
- [17] Fedele C, Singh A, Zerlanko BJ, et al. The alphavbeta6 integrin is transferred intercellularly via exosomes. *J Biol Chem.* **2015**;290(8):4545–4551.
- [18] Krishn SR, Singh A, Bowler N, et al. Prostate cancer sheds the alphavbeta3 integrin in vivo through exosomes. *Matrix Biol.* **2019**;77:41–57.
- [19] Lu H, Bowler N, Harshyne LA, et al. Exosomal alphavbeta6 integrin is required for monocyte M2 polarization in prostate cancer. *Matrix Biol.* **2018**;70:20–35.
- [20] Avraamides CJ, Garmy-Susini B, Varner JA. Integrins in angiogenesis and lymphangiogenesis. *Nat Rev Cancer.* **2008**;8(8):604–617.
- [21] Weis SM, Cheresh DA. alphaV integrins in angiogenesis and cancer. *Cold Spring Harb Perspect Med.* **2011**;1(1):a006478.
- [22] Cassoni P, Marrocco T, Bussolati B, et al. Oxytocin induces proliferation and migration in immortalized human dermal microvascular endothelial cells and human breast tumor-derived endothelial cells. *Mol Cancer Res.* **2006**;4(6):351–359.
- [23] Song J, Chen X, Wang M, et al. Cardiac endothelial cell-derived exosomes induce specific regulatory B cells. *Sci Rep.* **2014**;4:7583.
- [24] Tabata T, Kawakatsu H, Maidji E, et al. Induction of an epithelial integrin alphavbeta6 in human cytomegalovirus-infected endothelial cells leads to activation of transforming growth factor-beta1 and increased collagen production. *Am J Pathol.* **2008**;172(4):1127–1140.
- [25] Niu J, Li Z. The roles of integrin alphavbeta6 in cancer. *Cancer Lett.* **2017**;403:128–137. DOI: [10.1016/j.canlet.2017.06.012](https://doi.org/10.1016/j.canlet.2017.06.012)
- [26] Niu J, Li Z. The roles of integrin alphavbeta6 in cancer. *Cancer Lett.* **2017**;403:128–137.
- [27] Allen MD, Marshall JF, Jones JL. alphavbeta6 expression in myoepithelial cells: a novel marker for predicting DCIS progression with therapeutic potential. *Cancer Res.* **2014**;74(21):5942–5947.

- [28] Allen MD, Thomas GJ, Clark S, *et al.* Altered micro-environment promotes progression of preinvasive breast cancer: myoepithelial expression of alphavbeta6 integrin in DCIS identifies high-risk patients and predicts recurrence. *Clin Cancer Res.* 2014;20(2):344–357.
- [29] Moore KM, Thomas GJ, Duffy SW, *et al.* Therapeutic targeting of integrin alphavbeta6 in breast cancer. *J Natl Cancer Inst.* 2014;106:8.
- [30] Elayadi AN, Samli KN, Prudkin L, *et al.* A peptide selected by biopanning identifies the integrin alphavbeta6 as a prognostic biomarker for nonsmall cell lung cancer. *Cancer Res.* 2007;67(12):5889–5895.
- [31] Bates RC, Bellovin DI, Brown C, *et al.* Transcriptional activation of integrin beta6 during the epithelial-mesenchymal transition defines a novel prognostic indicator of aggressive colon carcinoma. *J Clin Invest.* 2005;115(2):339–347.
- [32] Cantor DI, Cheruku HR, Nice EC, *et al.* Integrin alphavbeta6 sets the stage for colorectal cancer metastasis. *Cancer Metastasis Rev.* 2015;34(4):715–734.
- [33] Dutta A, Li J, Lu H, *et al.* Integrin alphavbeta6 promotes an osteolytic program in cancer cells by upregulating MMP2. *Cancer Res.* 2014;74(5):1598–1608. .
- [34] Lu H, Wang T, Li J, *et al.* alphavbeta6 integrin promotes castrate-resistant prostate cancer through JNK1-mediated activation of androgen receptor. *Cancer Res.* 2016;76(17):5163–5174. .
- [35] Antonarakis ES, Carducci MA. Targeting angiogenesis for the treatment of prostate cancer. *Expert Opin Ther Targets.* 2012;16(4):365–376.
- [36] Bilusic M, Wong YN. Anti-angiogenesis in prostate cancer: knocked down but not out. *Asian. J. Androl.* 2014;16(3):372–377.
- [37] Melegh Z, Oltean S. Targeting angiogenesis in prostate cancer. *Int J Mol Sci.* 2019;20:11.
- [38] Sumpio BE, Yun S, Cordova AC, *et al.* MAPKs (ERK1/2, p38) and AKT can be phosphorylated by shear stress independently of platelet endothelial cell adhesion molecule-1 (CD31) in vascular endothelial cells. *J Biol Chem.* 2005;280(12):11185–11191.
- [39] Dutta A, Li J, Fedele C, *et al.* alphavbeta6 integrin is required for TGFbeta1-mediated matrix metalloproteinase2 expression. *Biochem J.* 2015;466(3):525–536.
- [40] Weinreb PH, Simon KJ, Rayhorn P, *et al.* Function-blocking integrin alphavbeta6 monoclonal antibodies: distinct ligand-mimetic and nonligand-mimetic classes. *J Biol Chem.* 2004;279(17):17875–17887.
- [41] Crescitelli R, Lasser C, Jang SC, *et al.* Subpopulations of extracellular vesicles from human metastatic melanoma tissue identified by quantitative proteomics after optimized isolation. *J Extracell Vesicles.* 2020;9(1):1722433.
- [42] Minciacchi VR, You S, Spinelli C, *et al.* Large oncosomes contain distinct protein cargo and represent a separate functional class of tumor-derived extracellular vesicles. *Oncotarget.* 2015;6(13):11327–11341.
- [43] Papetti M, Herman IM. Mechanisms of normal and tumor-derived angiogenesis. *Am J Physiol Cell Physiol.* 2002;282(5):C947–70.
- [44] Battle TE, Lynch RA, Frank DA. Signal transducer and activator of transcription 1 activation in endothelial cells is a negative regulator of angiogenesis. *Cancer Res.* 2006;66(7):3649–3657.
- [45] Huang S, Bucana CD, Van Arsdall M, *et al.* Stat1 negatively regulates angiogenesis, tumorigenicity and metastasis of tumor cells. *Oncogene.* 2002;21(16):2504–2512.
- [46] Li Z, Ren W, Zeng Q, *et al.* Effects of survivin on angiogenesis in vivo and in vitro. *Am J Transl Res.* 2016;8(2):270–283.
- [47] O'Connor DS, Schechner JS, Adida C, *et al.* Control of apoptosis during angiogenesis by survivin expression in endothelial cells. *Am J Pathol.* 2000;156(2):393–398. .
- [48] Sanhueza C, Wehinger S, Castillo Bennett J, *et al.* The twisted survivin connection to angiogenesis. *Mol Cancer.* 2015;14:198.
- [49] Breuss JM, Gallo J, DeLisser HM, *et al.* Expression of the beta 6 integrin subunit in development, neoplasia and tissue repair suggests a role in epithelial remodeling. *J Cell Sci.* 1995;108(Pt 6):2241–2251.
- [50] Koivisto L, Bi J, Hakkinen L, *et al.* Integrin alphavbeta6: structure, function and role in health and disease. *Int. J. Biochem. Cell. Biol.* 2018;99: 186–196.
- [51] Christofidou-Solomidou M, Bridges M, Murphy GF, *et al.* Expression and function of endothelial cell alpha v integrin receptors in wound-induced human angiogenesis in human skin/SCID mice chimeras. *Am J Pathol.* 1997;151(4):975–983.
- [52] Huang X, Wu J, Spong S, *et al.* The integrin alphavbeta6 is critical for keratinocyte migration on both its known ligand, fibronectin, and on vitronectin. *J Cell Sci.* 1998;111(Pt 15):2189–2195.
- [53] DeCicco-Skinner KL, Henry GH, Cataisson C, *et al.* Endothelial cell tube formation assay for the in vitro study of angiogenesis. *J Vis Exp.* 2014;91:e51312.
- [54] Hatzieremia S, Mohammed Z, McCall P, *et al.* Loss of signal transducer and activator of transcription 1 is associated with prostate cancer recurrence. *Mol Carcinog.* 2016;55(11):1667–1677.
- [55] Koth LL, Alex B, Hawgood S, *et al.* Integrin beta6 mediates phospholipid and collectin homeostasis by activation of latent TGF-beta1. *Am J Respir Cell Mol Biol.* 2007;37(6):651–659.
- [56] Munger JS, Huang X, Kawakatsu H, *et al.* The integrin alpha v beta 6 binds and activates latent TGF beta 1: a mechanism for regulating pulmonary inflammation and fibrosis. *Cell.* 1999;96(3):319–328.
- [57] Puthawala K, Hadjiangelis N, Jacoby SC, *et al.* Inhibition of integrin alpha(v)beta6, an activator of latent transforming growth factor-beta, prevents radiation-induced lung fibrosis. *Am J Respir Crit Care Med.* 2008;177(1):82–90.
- [58] Ferrari G, Cook BD, Terushkin V, *et al.* Transforming growth factor-beta 1 (TGF-beta1) induces angiogenesis through vascular endothelial growth factor (VEGF)-mediated apoptosis. *J Cell Physiol.* 2009;219(2):449–458.
- [59] Iruela-Arispe ML, Sage EH. Endothelial cells exhibiting angiogenesis in vitro proliferate in response to TGF-beta 1. *J Cell Biochem.* 1993;52(4):414–430.
- [60] Vinals F, Pouyssegur J. Transforming growth factor beta1 (TGF-beta1) promotes endothelial cell survival during in vitro angiogenesis via an autocrine mechanism implicating TGF-alpha signaling. *Mol Cell Biol.* 2001;21(21):7218–7230.
- [61] Penafuerte C, Bautista-Lopez N, Bouchentouf M, *et al.* Novel TGF-beta antagonist inhibits tumor growth and

angiogenesis by inducing IL-2 receptor-driven STAT1 activation. *J Immunol.* [2011](#);186(12):6933–6944.

- [62] Stobiecka M, Ratajczak K, Jakiela S. Toward early cancer detection: focus on biosensing systems and biosensors for an anti-apoptotic protein survivin and survivin mRNA. *Biosens Bioelectron.* [2019](#);137:58–71.
- [63] Deng H, Zhen H, Fu Z, et al. The antagonistic effect between STAT1 and survivin and its clinical significance in gastric cancer. *Oncol Lett.* [2012](#);3(1):193–199.