

# NRC Publications Archive Archives des publications du CNRC

# Scalable lentiviral vector production using stable HEK293SF producer cell lines

Manceur, Aziza P.; Kim, Howard; Misic, Vanja; Andreev, Nadejda; Dorion-Thibaudeau, July; Lanthier, Stéphan; Bernier, Alice; Tremblay, Sonia; Gélinas, Anne-Marie; Broussau, Sophie; Gilbert, Rénald; Ansorge, Sven

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

# Publisher's version / Version de l'éditeur:

https://doi.org/10.1089/hgtb.2017.086 Human Gene Therapy Methods, 2017-08-21

# NRC Publications Record / Notice d'Archives des publications de CNRC:

https://nrc-publications.canada.ca/eng/view/object/?id=a9ae2bd6-61d3-4eaf-bc53-d0f9ce7c86e2 https://publications-cnrc.canada.ca/fra/voir/objet/?id=a9ae2bd6-61d3-4eaf-bc53-d0f9ce7c86e2

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at <u>https://nrc-publications.canada.ca/eng/copyright</u> READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site https://publications-cnrc.canada.ca/fra/droits LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

**Questions?** Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

**Vous avez des questions?** Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.





# Scalable lentiviral vector production using stable HEK293SF producer cell lines

Aziza P. Manceur<sup>1</sup>, Howard Kim<sup>2</sup>, Vanja Misic<sup>2</sup>, Nadejda Andreev<sup>2</sup>, July Dorion-Thibaudeau<sup>1</sup>, Stéphane Lanthier<sup>1</sup>, Alice Bernier<sup>1</sup>, Sonia Tremblay<sup>1</sup>, Anne-Marie Gélinas<sup>1</sup>, Sophie Broussau<sup>1</sup>, Rénald Gilbert<sup>1</sup>, Sven Ansorge<sup>1</sup>

<sup>1</sup> Human Health Therapeutics, National Research Council Canada, Montreal, Quebec,

Canada

<sup>2</sup> BridGE, Centre for Commercialization of Regenerative Medicine, Toronto, Ontario,

Canada

**Corresponding author:** Sven Ansorge (sven.ansorge@cnrc-nrc.gc.ca), National Research Council Canada, Human Health Therapeutics, 6100 Royalmount, Montreal, QC, CAN H4P 2R2

Keyword: Lentiviral vector, stable producer, HEK293SF, perfusion, bioprocessing

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

Page 2 of 24

2

#### Abstract

Lentiviral vectors (LV) represent a key tool for gene and cell therapy applications. The production of these vectors in sufficient quantities for clinical applications remains a hurdle, prompting the field towards developing suspension processes that are conducive to large scale production.

We describe here a LV production strategy using a stable inducible producer cell line. The HEK293 cell line employed grows in suspension, thus offering direct scalability, and produces a Green Fluorescent Protein (GFP)-expressing lentiviral vector in the 10<sup>6</sup> Transduction Units (TU)/ml range without optimization. The stable producer cell line, called clone 92, was derived by stable transfection from a packaging cell line with a plasmid encoding the transgene GFP. The packaging cell line expresses all the other necessary components to produce LV upon induction with cumate and doxycycline.

First, we demonstrate that LV production using clone 92 is scalable from 20mL shake flasks to 3L bioreactors. Next, we developed two strategies for high yield LV production in perfusion mode using acoustic cell filter technology in 1 to 3L bioreactors. The first approach uses a basal commercial medium and perfusion mode both pre- and post-induction for increasing cell density and LV recovery. The second approach makes use of a fortified medium formulation to achieve target cell density for induction in batch mode, followed by perfusion mode after induction. Using these perfusion-based strategies, the titer was improved to  $3.2 \times 10^7$  TU/ml. As a result, cumulative functional LV titers were increased by up to 15-fold compared to batch mode, reaching a cumulative total yield of 8  $\times 10^{10}$  TU/L of bioreactor culture. This approach is easily amenable to large-scale production and commercial manufacturing.

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

#### 1. Introduction

Lentiviral vectors (LV) offer a number of valuable properties including stable gene integration into the host genome, the ability to transfer genetic information into dividing and non-dividing cells and a broad tissue tropism via VSV-G pseudotyping<sup>1</sup>. They are currently used in clinical trials to treat both rare and more frequent genetic and acquired diseases  $^{2-9}$ , as well as in CAR-T cell cancer therapy  $^{10,11}$ .

LVs are typically produced using adherent HEK293 cell lines by multi-plasmid transient transfection in serum-containing media. However, this methodology is labor-intensive, plasmid supply-dependent and not directly scalable. Adherent processes rather need to be scaled-out by increasing the available surface for cell attachment and growth <sup>12</sup>. Transient transfection also results in contaminations of the final product due to excess plasmids <sup>13</sup> and residual transfection reagent. As a result, stable LV producer cell lines have been generated. Successful approaches involve the use of an inducible system to circumvent cell death caused by the continuous expression of cytotoxic proteins (Gag, Rev and VSV-G)<sup>14</sup>. Most reports of stable producer cell lines have described adherent cell lines <sup>5,15,16</sup>, imposing constraints for scale-up and large scale production. These challenges have partially been overcome for other viral vectors through the use of highly intensified adherent cultures using single-use fixed bed bioreactors <sup>17-19</sup>. In parallel, several academic and industrial laboratories are working on the development of suspension-based production processes <sup>12,20,21</sup> which will eventually allow manufacturing of LV in classical stirred tank bioreactor facilities.

According to recently published reviews <sup>22,23</sup>, the field is moving towards the use of suspension processes for LV production. Indeed, the use of LV in therapeutic applications requires manufacturing of sufficient amounts of clinical and commercial high-quality supply in a reproducible way. Depending on the application and disease,  $1-40 \times 10^9$ infectious units of vector per patient are needed <sup>13</sup>; this increases the economic pressure and creates the need to develop high-yield production processes  $^{1,22}$ .

In the present study, we propose a LV production strategy using a stable inducible producer cell line derived from a packaging cell line we have previously described <sup>14</sup> and that grows in suspension in serum-free media. Induction of expression of the elements

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

necessary to produce LV occurs after the addition of cumate and doxycycline. Because of the notorious low stability of LV, we opted for the development of a production process in perfusion mode and evaluated two different strategies.

#### 2. Material and Methods

### 2.1 Cell Culture

The HEK293SF-LVP-CMVGFPq-92 cell line (abbreviated clone 92) was grown and maintained in SFM4TransFx293 (Hyclone), or in HyCell<sup>™</sup> TransFx-H media (Hyclone) which were both supplemented with 4mM L-Glutamine in all the experiments described in this study; HyCell<sup>™</sup> TransFx-H was also always completed with 0.1% poloxamer 188 which is a shear protectant used in high shear stress *environments*. Cell Boost 5<sup>™</sup> (CB5) Supplement (3.5 g/L) (Hyclone) is a chemically-defined feed and was supplemented only if indicated in the text. Cells were grown in suspension in shake flasks (Corning) with an agitation of 110 to 120rpm using orbital shakers (Infors HT), 5% CO2 at 37°C. Cell counts were performed with automated cell counters (Cedex Automated Cell Counter or NucleoCounter<sup>®</sup> NC-200<sup>™</sup>) or using a hemacytometer and erythrosine B. Cells were passaged regularly when reaching densities approaching 2 x 10<sup>6</sup> cells/mL.

# 2.2 Generation of stable producer cell line HEK293SF-LVP-CMVGFPq-92 (Clone 92) and induction of LV production

Plasmids used in this study were purified by chromatography using the maxiprep plasmid purification kit (Qiagen) by following the manufacturer's recommendations. The LV packaging cells used to generate HEK293SF-LVP-CMVGFPq-92 have been described previously and were obtained using the One-Shot strategy (i.e. all the LV components were added simultaneously in a single transfection) <sup>14</sup>. To generate clone 92, packaging cells (clone 29-6) grown in LC-SFM medium (Life Technologies) supplemented with 1% FBS (Hyclone) were co- transfected using Lipofectamine 2000 reagent (Life Technologies) with plasmid pCSII-CMV5-GFP previously linearized with *Stul* and with plasmid pCDNA6-hisA (Life Technologies) encoding the resistance for blasticidin previously linearized with *Xho*1

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

Human Gene Therapy

4

proof.

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

Human Gene Therapy

at a plasmid mass ratio ( $\mu$ g/ $\mu$ g) of 7:1. Two days after transfection, 7  $\mu$ g/mL of blasticidin (InvivoGen) was added to the culture medium and the cells were grown until a pool of blasticidin resistant cells was generated (about three weeks). The pool was then subcloned by limiting dilution in 96-well plates in medium without blasticidin. Clones were picked and first analysed for GFP expression. Clones with high levels of GFP expression were expanded and tested for the production of LV; LV production is initiated by inducing the cells through the addition of 1  $\mu$ g /mL of doxycycline and 30  $\mu$ g/mL of cumate. One of the best stable producer clones (clone 92) was adapted to grow in serum-free conditions in SFM4Transfx-293 medium (Hyclone), supplemented with 4 mM glutamine. A research cell bank was made in the same medium supplemented with 10% DMSO (Sigma).

#### 2.3 Stability study of Clone 92

Clone 92 was thawed in SFM4TransFx-293 and cultivated in suspension culture in 125 mL shaker flasks with 20 mL of culture volume. At 2, 6 and 10 weeks after thawing, cells were induced at a concentration of  $1.0 \times 10^6$  cells/mL for the production of LV. At 48 h post-induction, the medium was clarified by centrifugation and the supernatant containing the LV was supplemented with 1% FBS (as cryoprotectant) and then frozen at -80°C. The amount of LV in the supernatant was titrated simultaneously by Gene Transfer Assay (section 2.6).

### 2.4 LV production in shake flasks

In the first set of shake flask experiments, cells were seeded at  $0.2 \times 10^6$  cells/mL in SFM4TransFx293 medium. Once the cells reached a cell density of 1 to  $1.5 \times 10^6$  cells/mL, they were split into 50 mL aliquots in 250 mL shake flasks. Daily medium replacement (DMR) was performed for 5 consecutive days until induction by pelleting the cells by centrifugation (300g, 5 minutes) and resuspending them in different ratios (0-100%) of fresh versus spent medium. Cell counts and viability were determined with a Cedex

6

Automated Cell Counter after treating the cells for 30min with Accumax<sup>TM</sup> (Sigma) to reduce cell aggregation.

In the second set of experiments, cells were inoculated at a cell density of 0.3 x  $10^6$  cells/mL into 100 mL of complete HyCell<sup>TM</sup> TransFx-H media supplemented with 3.5g/L CB5 and batch cultured in a 500 mL shake flask. When cell density reached  $\geq$ 5E6 cells/mL, the cell suspension was split into 20 mL aliquots in 125 mL shake flasks and cells were induced (1 µg /mL of doxycycline and 30 µg/mL of cumate). Starting at 24 h after induction and every 24 h thereafter, cells were subjected to DMR at 50% with medium either supplemented with 3.5 g/L CB5 or not. The collected medium was filtered through a 0.45 µm filter and LV content was titrated by GTA. Daily cell counts and viability measurements were performed using the NucleoCounter<sup>®</sup> NC-200<sup>TM</sup>.

## 2.5 Bioreactor LV productions

The bioreactor setup used for the four batch runs, and perfusion run #1 was identical to the one used in a previous study <sup>12</sup>; similar conditions have been described earlier in detail <sup>24</sup>. In brief, a Chemap 3.5 L type SG bioreactor vessel (working volume 2.7 L) was equipped with probes to measure and control different parameters (temperature of 37°C, pH 7.05-7.1, dissolved oxygen (DO) 40%, and agitation of 80rpm). In perfusion mode, cells were retained in the bioreactor using a 10 L acoustic filter (AppliSens, Schiedam, Netherlands) operated in backflush mode (full recycling of cell suspension into bioreactor at each backflush) with an interval of 30 min and a run/stop ratio of 55/5 s (Figure 4). Cultures were grown up to ~1 to  $1.5 \times 10^6$  cells/mL in batch mode. Perfusion was started at 0.5 volume of medium per reactor volume per day (VVD), and increased to up to 1 VVD after induction. The culture was induced after reaching the targeted cell density (5×10<sup>6</sup> cells/mL) in perfusion mode.

For Perfusion #2-4, cells were inoculated at cell densities ranging from 0.25 to 0.35 x  $10^6$  cells/mL into 1 L of complete HyCell<sup>TM</sup> TransFx-H media (Hyclone) supplemented with 3.5 g/L CB5, and cultured in the BioFlo<sup>®</sup> 320 1 L stirred tank reactor in batch mode (37°C, pH 7.15, DO 40% and 80 RPM). Cells were induced at  $\ge 5 \times 10^6$  cells/mL. After induction,

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

proof

perfusion mode (1 VVD) was started with fresh medium containing inducers for 5 to 7 days. The miniBioSep (Applikon<sup>®</sup>) was used for cell retention (1 W power setting) during perfusion. Cell counts and viability measurements were performed using the NucleoCounter<sup>®</sup> NC-200<sup>™</sup> after daily sampling from the bioreactor. In all perfusion runs, harvests were collected and the LV-containing supernatant was kept on ice or at 4°C until clarification (once daily) and subsequently stored at -80 °C until quantification using the GTA assay. As two different bioreactor scales were used in this study, the total cumulative LV yield is normalized per liter of bioreactor culture (TU/L) to facilitate direct comparison.

# 2.6 Gene transfer assay (GTA) for lentiviral quantification

Functional viral titer (GTA titer) was determined using a flow cytometry-based gene transfer assay (GTA) as described previously with slight modifications <sup>12,21</sup>. In brief, HEK293A or 293T cells were cultured in DMEM containing 5% FBS and 2 mM L-Glutamine. The cells were seeded at a density of 1E05 cells/well of a 24-well plate 5 hours before transduction with LV. Prior to transduction, LV samples were serially diluted in DMEM supplemented with 8  $\mu$ g/mL of polybrene and incubated at 37°C for 30 min. Transduction was performed by removing culture medium, adding 200µl diluted LV to cells and incubating over night at 37°C. Next day, 800μl culture medium was added to each well and cells were incubated for an additional 48 hours prior to flow cytometry to quantify GFP expressing cells. Therefore, GFP was measured 3 days post-transduction. Note that the GFP signal measured is truly due to transgene expression and not to the presence of episomes since a similar signal was measured 10 days post-transduction in a control experiment (supplementary Fig. 1). The titer (TU/mL) is determined using the formula [(% of GFP positive cells/100) x (number of cells transduced) x (dilution factor) x (1mL / volume transduced)]. An in-house LV standard was used in all measurements to minimize interassay variability.

7

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

#### 3. Results

#### 3.1 Generation and stability of a stable producer cell line (Clone 92)

A packaging cell line that contains all the necessary components to produce LV, except for the LV genomic RNA, has been described previously<sup>14</sup>. Briefly, all the LV components (Gag/Pol, Rev, and VSV-G) were added simultaneously through a single transfection event to generate a packaging cell line named PacLV. In the packaging cells, transcription of Rev and the envelope protein (VSV-G) is under the control of the tetracycline and cumate switches, which means that addition of doxycycline and cumate in the culture medium is required to induce the production of LV (Fig. 1A). Gag/Pol is under the control of a CMV promoter. Even though the expression of Gag/Pol is constitutive and not directly controlled by the switches, its expression depends on the presence of REV because of a REV Responsive Element (RRE). A cell line (known as producer) that contains all the elements necessary to produce LV including the genomic RNA was then constructed. For ease of titration, we chose to construct producer for LV expressing GFP regulated by the strong constitutive CMV promoter. This was done by co-transfecting the packaging cells with the transfer vector pCSII-CMV5-GFPq, which also contains a RRE. Details about the plasmid construction were previously reported<sup>14</sup>. The producer cell line selected was named clone 92. To confirm that the production of LV from clone 92 was stable, the cells were cultivated for 10 weeks in shake flasks and the production of LV was monitored at different time points after induction. LV titers above  $3.0 \times 10^6$  TU/mL were maintained throughout this period of time, indicating that clone 92 is stable (Figure 1B).

### 3.2 LV production in bioreactors operated in batch mode

In order to evaluate the performance of clone 92 in stirred tank bioreactors, 4 batch cultivations were performed at the 3.5 L scale (Fig. 2) in SFM4TransFx293 media, our starting basal medium for this cell line. The viability profile after induction was showing a reproducible decline, reaching 70-80% on 3 days post-induction (dpi) (Fig. 2A). Functional LV titer production kinetics exhibit a reproducible peak on 3 dpi with an average titer of 6 x  $10^6$  TU/mL (Fig. 2B). Production was found to be directly scalable from shake flasks to

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

bioreactors in batch mode, with comparable production profiles (Fig. 2C). The total LV yield per liter of culture was of  $6 \times 10^9$  TU on average (Fig. 2D), with a specific production of 4.4 TU/cell.

### 3.3 LV production in small scale

In order to address the low stability of LV, we planned to use continuous harvesting in perfusion mode to rapidly recover produced LV. As a model, two strategies were explored in shake flasks. First, experiments were performed to determine the effect of daily medium replacement (DMR) during the cell growth phase and to test the impact of higher cell density at induction on production yield. Cells were centrifuged once daily, and 0 to 100% of the spent medium was replaced by fresh SFM4Transfx293 medium between -3dpi and Odpi. Results show that the growth phase could be extended through the daily addition of increasing amounts of fresh medium; a cell density of above  $8 \times 10^6$  cells/mL was reached at Odpi through complete daily medium replacement over 4 days (Figure 3A), which is 3 times more than the batch control. Following induction, LV was quantified at 3dpi. Titer was significantly increased by media replacement going from  $1.0 \times 10^6$  TU/mL without DMR to  $3.35 \times 10^7$  TU/mL when 75% to 100% of the spent medium was replaced with fresh medium (Fig. 3B). A better specific production was measured with 75% DMR compared to 100% DMR. This indicates that an optimal cell density at induction for LV production under the conditions used is the one obtained with 75% DMR, which is approximately  $5.5 \times 10^6$  cells/mL.

Therefore, a cell density at induction of 5 x 10<sup>6</sup> cells/mL was targeted in the second set of small scale experiments. A hybrid system combining the use of a fortified medium during the cell growth phase and DMR during the production phase was tested. A new medium formulation that does not contain hydrolysates and promises a lower lot-to-lot variability (HyCell<sup>™</sup> TransFx-H) was chosen. In our hands, the LV titers were similar between SFM4TransFx293 and HyCell<sup>™</sup> TransFx-H when induction took place at 5 x 10<sup>6</sup> cells/mL after daily medium replacement of 75% (supplementary table 1).

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

Page 10 of 24

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

Human Gene Therapy

In order to support growth to high cell density in batch mode, HyCell<sup>™</sup> TransFx-H was supplemented with Cell Boost 5 (CB5) and cells were grown to 5 x 10<sup>6</sup> cells/mL until induction; 50% daily media replacement took place during the production phase with or without CB5 addition (Fig. 3C). Similar functional LV titers were obtained at 50% DMR with or without CB5 from 1 dpi to 3 dpi. However, supplementing with CB5 improved the daily titer on 4 dpi and 5 dpi (Fig. 3D). Taken together, these data suggest that expanding cells in a fortified medium (HyCell<sup>™</sup> TransFx-H with CB5) results in cell densities similar to what is obtained in perfusion mode with simplified bioreactor operation until induction. In addition, adding CB5 during the production phase prolongs the production phase, presumably by improving cell viability.

#### 3.4 Improved production in perfusion mode

Based on the results obtained in shake flasks, parameters were selected for bioreactor productions performed in perfusion mode. A schematic of the set-up used to operate in perfusion mode is shown (Fig. 4). The first run (Perfusion 1), was performed using SFM4TransFx293 medium for growth and production in a 3.5L stirred tank bioreactor and is used as a reference. Perfusion was started at 0.5 volume of medium per reactor volume per day (VVD), and increased to up to 1 VVD after induction.

In an effort to simplify the process, three additional runs (Perfusion 2-4) were operated using a hybrid mode similar to what was performed in shake flasks; cells were expanded in 1 L of HyCell<sup>™</sup> TransFx-H media supplemented with CB5 in batch mode. Cultures were induced at densities≥5x10<sup>6</sup> cells/mL and perfusion mode was started (1 VVD) with fresh medium containing CB5 and inducers. The cell density and viability of Perfusion 1 is significantly different from Perfusion 2-4 after induction (Fig. 5A-B); the viability dropped quickly after induction, similarly to what was observed in cultures without CB5 supplementation (Figs. 2A, 3A and C), and the run was stopped at 5 dpi when the viability reached 25%. In contrast, the viable cell density of Perfusion runs 2-4 showed no growth arrest and increased up to 17x10<sup>6</sup> cells/mL after induction; viability remained above 80% until harvest (Fig. 5A-B). The peak in titer (2-3 x 10<sup>7</sup> TU/mL) was observed at 3 dpi for

10

Perfusion 1 whereas it was at 4 dpi for Perfusion 2-4 (Fig. 5C). Cumulative titers of the 4 perfusion runs are in a similar range of  $5-8 \times 10^{10}$  TU/L with the cumulative titer of Perfusion 1 being highest (Fig. 5D). The titers measured in the bioreactor versus the harvest vessel are comparable (supplementary Fig. 2).

Compared to the batch cultures, the average peak titer measured in the harvest for the 4 perfusion runs ( $2.2 \times 10^7 \text{ TU/mL}$ ) is nearly 4-fold higher than the one obtained in batch mode ( $6 \times 10^6 \text{ TU/mL}$ ) (Fig. 2B). Furthermore, on average, 11 times more total LV (up to 8 x  $10^{10} \text{ TU/L}$ ) is obtained in perfusion mode compared to batch mode because of the daily harvests (Fig. 5B). The viable cell density at time of induction was between 1 and  $1.5 \times 10^6$  cells/mL in batch, whereas it was  $5.4 \times 10^6$  cells/mL in perfusion. The specific production was also improved in perfusion with an average of 11.5 TU/cell compared to 4.4 TU/cell in batch mode.

## 4. Discussion

Using a stable producer cell line (clone 92), we have developed two strategies for high yield LV production in perfusion mode. The first approach uses the basal medium SFM4TransFx293 and perfusion mode for both increasing cell density and LV recovery (Figs. 3A-B and 5A-B). The second approach made use of a new medium formulation (HyCell<sup>™</sup> TransFx-H) in combination with medium fortification through CB5 addition: this approach might be simpler to operate since the perfusion mode is only started after induction (Figs. 3C-D and 5C-D). Overall, we were able to increase the cumulative yield of LV to up to 15-fold compared to batch mode. Although we expect that the absolute LV titers of 8 x 10<sup>10</sup> TU/L are transgene-dependent, we hypothesize that the yield improvements of more than 1 log compared to batch mode will be transferable to other transgenes.

A few adherent stable producer cell lines have been described with LV titers in the range of  $1 \times 10^{6}$  to  $1.5 \times 10^{8}$  <sup>25-27</sup>. However, adherent cell lines present significant limitations for large scale productions. In the strategy employed here, the mother cell line (HEK293SF-

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

12

3F6) used to generate the packaging cell line and subsequently the stable producer, was already adapted to suspension and serum-free conditions<sup>28</sup>. A key element for the successful generation of clone 92 was the use of a double switch system; two inducers are required to initiate the synthesis of LV, which offers a tight control on the production of LV cytotoxic elements. Early attempts using only one switch were not successful (results not shown). The producer cell line reported here is grown in suspension but further process optimization could be pursued. For example, CB5 addition seemed to extend the window of high LV titers (>10<sup>7</sup> TU/mL) to beyond 4-5 dpi and also slowed down the decline in culture viability while maintaining cell growth after induction. CB5 contains several nutrients that support cell viability, but may have some components (e.g. growth factors) that may be counter-productive to vector output. Indeed, comparing CB5 addition to its absence during induction in shake flasks, LV titers are at comparable levels but much lower on a per-cell basis with CB5 (Fig. 3C,D). It is envisioned that this system could be manipulated to balance LV production (a cytotoxic process) and cell maintenance to develop a continuous LV production model. In contrast, production in the basal medium SFM4TransFx293 without supplementation led to a faster release of LV until 3 dpi (Fig. 4 C and D). A combination of CB5 supplementation during the growth phase and removal of CB5 during the production phase could lead to a further increase in production yields at earlier time points. An extensive metabolite analysis and further CB5 titration could also be beneficial and support induction at higher cell densities.

The recovery after purification and downstream processing will also affect the final functional titers <sup>29,30</sup>. We are currently investigating the use of column/membrane chromatography to decrease the amount of impurities in the final product as published by other teams <sup>21,31,32</sup>. Purification should also aim at removing the two inducers used in this study. Cumate is known for being non-cytotoxic<sup>33</sup> but doxycycline is an antibiotic of the tetracycline class. Therefore, this could be an issue for people with tetracycline allergies if traces are present in the final product.

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

Page 13 of 24

proof.

In conclusion, to the best of our knowledge, this study is the first to describe process development and improvement efforts for a stable LV producer suspension HEK293 cell line. The process described was reproducible and robust from small-scale to 1-3 L bioreactor scale. Two strategies for improvement of the cumulative LV yield were tested; both of these employed acoustic cell filter technology to operate bioreactor cultures in perfusion mode. Overall, an increase in cumulative LV titer (TU per L of bioreactor culture) of more than 1 log was achieved. This means that we were able to produce up to 8 x 10<sup>10</sup> TU/L bioreactor volume in perfusion mode. We expect that the developed production process is easily amenable to large-scale production and commercial manufacturing.

**Acknowledgements:** The authors would like to acknowledge the contribution of Julia Transfiguracion, Adam McLeod, Nick Timmins, Aaron Dulgar-Tulloch, Mélanie Simoneau, and Nazila Nazemi-Moghaddam to this work. Work performed at CCRM was co-funded by FedDev Ontario (Advanced Manufacturing Fund) and GE Healthcare.

Author Disclosure Statement: No competing financial interests exist

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

#### References

- 1. Segura MM, Mangion M, Gaillet B, Garnier A. New developments in lentiviral vector design, production and purification. *Expert Opin Biol Ther.* 2013;13(7):987-1011.
- Blits B, Petry H. Perspective on the Road toward Gene Therapy for Parkinson's Disease. Front Neuroanat. 2016;10:128.
- 3. Brown BD, Cantore A, Annoni A, et al. A microRNA-regulated lentiviral vector mediates stable correction of hemophilia B mice. *Blood.* 2007;110(13):4144-4152.
- Cavazzana M, Six E, Lagresle-Peyrou C, Andre-Schmutz I, Hacein-Bey-Abina S. Gene Therapy for X-Linked Severe Combined Immunodeficiency: Where Do We Stand? *Hum Gene Ther.* 2016;27(2):108-116.
- 5. Greene MR, Lockey T, Mehta PK, et al. Transduction of human CD34+ repopulating cells with a self-inactivating lentiviral vector for SCID-X1 produced at clinical scale by a stable cell line. *Hum Gene Ther Methods.* 2012;23(5):297-308.
- 6. Malik P, Arumugam PI, Yee JK, Puthenveetil G. Successful correction of the human Cooley's anemia beta-thalassemia major phenotype using a lentiviral vector flanked by the chicken hypersensitive site 4 chromatin insulator. *Ann N Y Acad Sci.* 2005;1054:238-249.
- May C, Rivella S, Callegari J, et al. Therapeutic haemoglobin synthesis in betathalassaemic mice expressing lentivirus-encoded human beta-globin. *Nature*. 2000;406(6791):82-86.
- 8. Pawliuk R, Westerman KA, Fabry ME, et al. Correction of sickle cell disease in transgenic mouse models by gene therapy. *Science*. 2001;294(5550):2368-2371.
- 9. Ribeil JA, Hacein-Bey-Abina S, Payen E, et al. Gene Therapy in a Patient with Sickle Cell Disease. *N Engl J Med.* 2017;376(9):848-855.
- 10. Levine BL, Miskin J, Wonnacott K, Keir C. Global Manufacturing of CAR T Cell Therapy. *Mol Ther Methods Clin Dev.* 2017;4:92-101.
- 11. Sadelain M, Brentjens R, Riviere I. The basic principles of chimeric antigen receptor design. *Cancer Discov.* 2013;3(4):388-398.
- 12. Ansorge S, Lanthier S, Transfiguracion J, Durocher Y, Henry O, Kamen A. Development of a scalable process for high-yield lentiviral vector production by

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

Page 15 of 24

proof

transient transfection of HEK293 suspension cultures. *J Gene Med.* 2009;11(10):868-876.

- 13. Sanber KS, Knight SB, Stephen SL, et al. Construction of stable packaging cell lines for clinical lentiviral vector production. *Sci Rep.* 2015;5:9021.
- Broussau S, Jabbour N, Lachapelle G, et al. Inducible packaging cells for large-scale production of lentiviral vectors in serum-free suspension culture. *Mol Ther.* 2008;16(3):500-507.
- 15. Sinn PL, Sauter SL, McCray PB, Jr. Gene therapy progress and prospects: development of improved lentiviral and retroviral vectors--design, biosafety, and production. *Gene Ther.* 2005;12(14):1089-1098.
- 16. Stornaiuolo A, Piovani BM, Bossi S, et al. RD2-MolPack-Chim3, a packaging cell line for stable production of lentiviral vectors for anti-HIV gene therapy. *Hum Gene Ther Methods.* 2013;24(4):228-240.
- 17. Lesch HP, Heikkila KM, Lipponen EM, et al. Process Development of Adenoviral Vector Production in Fixed Bed Bioreactor: From Bench to Commercial Scale. *Hum Gene Ther.* 2015;26(8):560-571.
- Powers AD, Piras BA, Clark RK, Lockey TD, Meagher MM. Development and Optimization of AAV hFIX Particles by Transient Transfection in an iCELLis((R)) Fixed-Bed Bioreactor. *Hum Gene Ther Methods.* 2016;27(3):112-121.
- 19. Wang X, Olszewska M, Qu J, et al. Large-scale clinical-grade retroviral vector production in a fixed-bed bioreactor. *J Immunother.* 2015;38(3):127-135.
- 20. Gutierrez-Granados S, Cervera L, Segura Mde L, Wolfel J, Godia F. Optimized production of HIV-1 virus-like particles by transient transfection in CAP-T cells. *Appl Microbiol Biotechnol.* 2016;100(9):3935-3947.
- 21. Segura MM, Garnier A, Durocher Y, Coelho H, Kamen A. Production of lentiviral vectors by large-scale transient transfection of suspension cultures and affinity chromatography purification. *Biotechnol Bioeng.* 2007;98(4):789-799.
- 22. McCarron A, Donnelley M, McIntyre C, Parsons D. Challenges of up-scaling lentivirus production and processing. *J Biotechnol.* 2016;240:23-30.
- 23. Merten OW, Hebben M, Bovolenta C. Production of lentiviral vectors. *Mol Ther Methods Clin Dev.* 2016;3:16017.

15

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this I

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

16

- Henry O, Dormond E, Perrier M, Kamen A. Insights into adenoviral vector production kinetics in acoustic filter-based perfusion cultures. *Biotechnol Bioeng.* 2004;86(7):765-774.
- Lee CL, Chou M, Dai B, Xiao L, Wang P. Construction of stable producer cells to make high-titer lentiviral vectors for dendritic cell-based vaccination. *Biotechnol Bioeng*. 2012;109(6):1551-1560.
- 26. Wielgosz MM, Kim YS, Carney GG, et al. Generation of a lentiviral vector producer cell clone for human Wiskott-Aldrich syndrome gene therapy. *Mol Ther Methods Clin Dev.* 2015;2:14063.
- 27. Xu K, Ma H, McCown TJ, Verma IM, Kafri T. Generation of a stable cell line producing high-titer self-inactivating lentiviral vectors. *Mol Ther.* 2001;3(1):97-104.
- Cote J, Garnier A, Massie B, Kamen A. Serum-free production of recombinant proteins and adenoviral vectors by 293SF-3F6 cells. *Biotechnol Bioeng*. 1998;59(5):567-575.
- 29. Bandeira V, Peixoto C, Rodrigues AF, et al. Downstream processing of lentiviral vectors: releasing bottlenecks. *Hum Gene Ther Methods*. 2012;23(4):255-263.
- 30. Ausubel LJ, Hall C, Sharma A, et al. Production of CGMP-Grade Lentiviral Vectors. *BioProcess international.* 2012;10(2):32-43.
- 31. Merten OW, Charrier S, Laroudie N, et al. Large-scale manufacture and characterization of a lentiviral vector produced for clinical ex vivo gene therapy application. *Hum Gene Ther.* 2011;22(3):343-356.
- 32. Kutner RH, Puthli S, Marino MP, Reiser J. Simplified production and concentration of HIV-1-based lentiviral vectors using HYPERFlask vessels and anion exchange membrane chromatography. *BMC Biotechnology*. 2009;9(1):1-7.
- 33. Poulain A, Perret S, Malenfant F, Mullick A, Massie B, Durocher Y. Rapid protein production from stable CHO cell pools using plasmid vector and the cumate geneswitch. *J Biotechnol.* 2017;255:16-27.

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

Human Gene Therapy

proof



**Figure 1:** Schematic of the cumate-inducible system and stability of clone 92. A) In the packaging cells and thus also clone 92, transcription of Rev and the envelope protein (VSVG) is under the control of the tetracycline and cumate switches; addition of doxycycline and cumate in the culture medium is required to induce the production of LV. Cumate, prevents binding of the cumate repressor (CymR) to the cumate operator (CuO).Doxycycline promotes binding of the reverse tetracycline transactivator (rtTA2s-M2) to the tetracycline promoter (TR5). B) To test the stability of clone 92, the cells were maintained in suspension culture without selective pressure for 10 weeks. After two, six and ten weeks of culture, a portion of the cumate. The amount of LVs produced at 48 h post-induction was analyzed by Gene Transfer Assay (GTA) in triplicates (Error bars are standard deviation).

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)



**Figure 2:** Results obtained in 3L bioreactor runs operated in batch mode. A) Viable cell count (black line) and viability (grey line) measured in 4 independent bioreactor runs (Batch 1 to Batch 4) operated in batch mode using SFM4TransFx293 medium. B) Functional titer kinetics for 4 batch runs up to 3 days post-induction. C) Functional LV titers on 3 dpi for 4 independent batch productions and related shake flask controls. The internal control was obtained by sampling an aliquot from the bioreactor shortly after induction. This aliquot was then transferred into and kept in a shake flask during the LV production phase. The external control was performed in parallel in shake flask throughout the experiment during both the growth phase and LV production phase. D) Total functional titer produced per 1 L batch culture for 4 batch runs

Human Gene Therapy

Human Gene Therapy Methods Scalable lentiviral vector production using stable HEK293SF producer cell lines (doi: 10.1089/hgtb.2017.086) This article has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof. Downloaded by Cisti Consortia from online.liebertpub.com at 08/24/17. For personal use only.

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)



Figure 3: Results obtained in shake flasks. A) Viable cell count (black line) and viability (grey line) between -4dpi and 3dpi upon daily media replacement (DMR) at 0-100% in SFM4TransFx293 medium. Medium replacement took place on -3dpi, -2dpi, -1dpi and 0dpi in duplicate shake flasks. B) LV titer was measured by Gene Transfer Assay (GTA) at 3dpi for samples in duplicate shown in panel A (error bars are standard deviation). C) Viable cell count and viability of cells in HyCell<sup>™</sup> TransFx-H media supplemented with 3.5g/L Cell Boost 5<sup>™</sup> Supplement (CB5) (Squares) or without CB5 (Circles). For each LV producer cell suspension, DMR was performed at 50% with fresh media, either supplemented with CB5 or not (n=2 independent shake flasks for both conditions) every 24 h following induction. D) The functional titer (TU/mL) was assayed for each of the harvests shown in panel C for both conditions by GTA (Error bars are standard deviation).



**Figure 4:** Schematic showing the set-up used in perfusion mode. Cells are transferred into the bioreactor vessel using the inoculation bottle at 0.25-0.35E06 cells/ml. Cell-free daily harvests and samplings are performed using the harvest bottle and the associated sampler under sterile conditions (cells are retained using an acoustic filter and are recirculated into the bioreactor while the supernatant is harvested). The sampler on the left hand side is used to sample cells daily to measure cell density and viability. Medium is kept at  $4^{\circ}$ C and pumped into the vessel so that 0.5 to 1 volume of medium per reactor volume vessel is added over 24 hours; the exact volume of media added is further monitored using a scale and a level detector. Oxygen (pO<sub>2</sub>), temperature and pH are monitored with sterilizable probes. The pH is kept between 7.05 and 7.1 through the addition of CO<sub>2</sub> via the surface or the addition of a base (NaHCO<sub>3</sub>). Peristaltic pumps are also shown on the schematic (reversed triangle in a circle).

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof

Human Gene Therapy Methods or production using stable HEK293SF producer cell lines (doi: 10.1089/hgtb.2017.086) lication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof. Cisti Consortia from online. liebertpub.com at 08/24/17. For personal use only.

Scalable lentiviral vector This article has been peer-reviewed and accepted for public Downloaded by C 20

Human Gene Therapy Methods Scalable lentiviral vector production using stable HEK293SF producer cell lines (doi: 10.1089/hgtb.2017.086) This article has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof. Downloaded by Cisti Consortia from online.liebertpub.com at 08/24/17. For personal use only.

Human Gene Therapy

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

3.5L scale.

The cumulative titers were calculated for 1L harvests for all the runs

(perfusion filtrate collected on ice) from the 4 independent runs using the GTA assay. D)

cell counts (VCC) and B) cell viability prior to and after induction of virus production at 1 to

C) Functional LV titer (TU/mL) was assayed from each of the daily harvests

Figure 5: Cell viability and titers measured in 4 independent perfusion cultures. A) Viable

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof.



Page 21 of 24

22

at 3dpi by GTA. approximately 5x 10<sup>6</sup> cells/mL was reached and cells were induced. Titers were measured replacement at a rate of 75% was performed on consecutive days until a cell density of Supplementary Table 1: LV titers measured in two different culture media. Medium

Scalable lentiviral vector production using stable HEK293SF producer ce This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and	ell lines proof c	(DOI: 1 orrecti	10.1089 ion. The	)/hgtb.: e final p	2017.0 oublish	86) ed versi	ion ma	y diffe	from th	nis pr	roof.
	* Without CB5	media*	HyCell TransFx-H		SFM4TransFx293			Media	at 3dpi by GTA.		approximately 5x 10 <sup>4</sup>
		Flask 4	Flask 3	Flask 2	Flask 1			Flask ID #			<sup>5</sup> cells/mL was i
		4.86	5.01	5.62	5.08	cells/mL)	induction (E06	Cell density at			reached and cells v
		8.03 x 10 <sup>7</sup>	7.73 x 10 <sup>7</sup>	1.05 x 10 <sup>8</sup>	9.33 x 10 <sup>7</sup>			Titer (TU/mL)			vere induced. Tite
		16.5	15.4	18.7	18.4		productivity	Specific			rs were measured

Human Gene Therapy

Human Gene Therapy Methods Scalable lentiviral vector production using stable HEK293SF producer cell lines (doi: 10.1089/hgtb.2017.086) This article has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof. Downloaded by Cisti Consortia from online.liebertpub.com at 08/24/17. For personal use only.

Human Gene Therapy Methods Scalable lentiviral vector production using stable HEK293SF producer cell lines (doi: 10.1089/hgtb.2017.086) This article has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof. Downloaded by Cisti Consortia from online.liebertpub.com at 08/24/17. For personal use only.

Human Gene Therapy

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof.



corresponding to 3 different dilutions. two time points. Error bars are standard deviations of 3 measurements per sample days or 10 days post-transduction. No significant difference was observed between the Supplementary Figure 1: Quantification of GFP-expressing cells was performed either 3

Human Gene Therapy Methods Scalable lentiviral vector production using stable HEK293SF producer cell lines (doi: 10.1089/hgtb.2017.086) This article has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof. Downloaded by Cisti Consortia from online.liebertpub.com at 08/24/17. For personal use only.

Human Gene Therapy

Scalable lentiviral vector production using stable HEK293SF producer cell lines (DOI: 10.1089/hgtb.2017.086)

This paper has been peer-reviewed and accepted for publication, but has yet to undergo copyediting and proof correction. The final published version may differ from this proof.



(D). vessel (open square) and the harvest (full circle) for run 1 (A), run 2 (B), run 3 (C) and run 4 Supplementary Figure 2: LV titer was measured by GTA from 1dpi to 7dpi in the bioreactor

24