

Accepted Manuscript

Title: Comparative analysis and generation of a robust HIV-1 DNA quantification assay

Authors: Jordan Thomas, Alessandra Ruggiero, Francesco A Procopio, Giuseppe Pantaleo, William A Paxton, Georgios Pollakis



PII: S0166-0934(18)30378-1
DOI: <https://doi.org/10.1016/j.jviromet.2018.10.010>
Reference: VIRMET 13551

To appear in: *Journal of Virological Methods*

Received date: 31-7-2018
Revised date: 11-10-2018
Accepted date: 12-10-2018

Please cite this article as: Thomas J, Ruggiero A, Procopio FA, Pantaleo G, Paxton WA, Pollakis G, Comparative analysis and generation of a robust HIV-1 DNA quantification assay, *Journal of Virological Methods* (2018), <https://doi.org/10.1016/j.jviromet.2018.10.010>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Comparative analysis and generation of a robust HIV-1 DNA quantification assay

Running title: Robust method for HIV-1 DNA Quantification

Jordan Thomas,^a Alessandra Ruggiero,^a Francesco A Procopio,^b Giuseppe Pantaleo,^b

William A Paxton,^a and Georgios Pollakis.^{a,#}

^aDepartment of Clinical Infection, Microbiology and Immunology (CIMI), Institute of Infection and Global Health (IGH), University of Liverpool, Liverpool, United Kingdom

^bService of Immunology and Allergy, Lausanne University Hospital, University of Lausanne, Lausanne, Switzerland

#Corresponding author

Georgios Pollakis

Ronald Ross Building

8 West Derby Street

Liverpool, L687BE

United Kingdom

+44(0)1517959681

g.pollakis@liverpool.ac.uk

Highlights

- Non-replicative J-Lat clones are the most suitable cell types for HIV-1 DNA quantification standards
- Strong correlation between assays when quantifying low copy patient samples indicating that assays may be used interchangeably in different clinical settings
- Assay performance is significantly affected by sequence variation within patient samples
- HIV-1 quantification assay performance has been improved by the introduction of two new forward primers

ABSTRACT HIV-1 infection cannot be cured due to the presence of the latent reservoir (LR). Novel cure or treatment strategies, such as “shock and kill” or therapeutic vaccination, aim to reduce or eradicate the LR. Cure strategies utilise robust DNA quantification assays to measure the change in the LR in low copy scenarios. No standard assay exists, which impedes the reliable comparison of results from different therapy and vaccine trials and HIV-1 total DNA quantification methods have not been previously compared. The HIV-1 long terminal repeat (LTR) has been shown to be the best target for DNA quantification. We have analysed two HIV-1 quantification assays, both able to differentiate between the variant HIV-1 DNA forms via the use of pre-amplification and primers targeting LTR. We identify a strong correlation ($r=0.9759$, $P<0.0001$) between assays which is conserved in low copy samples ($r=0.8220$, $P<0.0001$) indicating that these assays may be used interchangeably. The RvS assay performed significantly ($P=0.0021$) better than the CV assay when quantifying HIV-1 total DNA in patient CD4+ T lymphocytes. Sequence analysis demonstrated that viral diversity can limit DNA quantification, however *in silico* analysis of the primers indicated that within the target region nucleotide miss-matches appear infrequently. Further *in silico* analysis using up to-date sequence information led to the improvement of primers and enabled us to establish a more broadly specific assay with significantly higher HIV-1 DNA quantification capacity in patient samples ($p=0.0057$, $n=17$).

Abbreviations: RvS, Rene van der Sluis assay; CV, Claire Vandergeeten assay; CRx, Christine Rouzioux

Key Words: HIV-1; DNA quantification; Reservoir; cure; therapeutic vaccines

1. Introduction

The development of active antiretroviral therapy (ART) has been a major breakthrough in the treatment of human immunodeficiency virus type 1 (HIV-1) infection, effectively preventing the progression to acquired immunodeficiency syndrome (AIDS) (Brechtel et al., 2001). Despite this, ART cannot completely eradicate the virus due to the presence of a replication competent latent reservoir (LR) in different cell populations including long-lived resting CD4⁺ T cells that harbour pro-viral DNA integrated into the genome (Chun et al., 1997a; Finzi et al., 1997). Such infected cells can produce replication competent HIV-1, supporting rapid viral rebound following ART interruption (Davey et al., 1999; Joos et al., 2008; Rothenberger et al., 2015). Research is therefore focused on the development of novel approaches to reduce or eliminate the LR, with the aim of developing a functional cure for HIV-1 infection.

Therapeutic vaccination, administered during ART mediated virus suppression aims to stimulate the production of broad and effective immune responses, inducing sustained immune control of HIV-1 in the absence of therapy. A number of studies have explored the therapeutic potential of vaccination in both simian immunodeficiency virus (SIV) models (De Rose et al., 2008; Fuller et al., 2012; Fuller et al., 2006; Hel et al., 2002; Hel et al., 2000; Lu et al., 2003) and in human trials (Barouch et al., 2013; Garcia et al., 2013; Lévy et al., 2014; Lu et al., 2004) with vaccine agents including DNA based vaccines expressing antigen, viral

vectors expressing antigen, passive transfer immunotherapy, dendritic cells (DC) primed for HIV-1 antigen presentation or combinations of these (Mylvaganam, Silvestri, and Amara, 2015). Generally, these studies have demonstrated that therapeutic vaccination can achieve reduced viral loads, increased time to viral rebound, reduction in size of the LR and in inducing stronger and more sustained immune response against HIV-1 (Mylvaganam et al., 2015). Alternatively, strategies which aim to completely eradicate the HIV-1 LR are popular in current research and clinical trials (Kim, Anderson, and Lewin, 2018). These “shock and kill” approaches utilise latency reversing agents (LRAs) to induce activation of latently infected cells in the presence of ART, rendering those cells susceptible to cytolysis or immune clearance whilst limiting the chance of subsequent rounds of infection (Archin et al., 2017; Archin et al., 2012; Elliott et al., 2015; Margolis et al., 2016). Adding to this, recent approaches have explored the potential of a “lock in and apoptosis” strategy that when combined with the LRAs, utilises a novel compound to antagonise the viral gag protein and prevent virus budding whilst still inducing virus apoptosis (Tateishi et al., 2017).

Research focused on the reduction or elimination of the LR must utilise robust assays that can reliably and reproducibly measure the effect that the treatment or vaccine strategy has on the size of the LR. The quantification of HIV-1 DNA from peripheral blood mononuclear cells (PBMC) of patients via polymerase chain reaction (PCR) provides a useful tool to monitor the size of the viral reservoir and distinguish between different viral life-cycle stages. The initial assays were based around quantitative PCR measurements and adapted to be able to distinguish between single and 2-LTR circular forms (Kostrikis et al., 2002; Sharkey et al., 2000). These assays have subsequently been adapted, targeting different regions of the HIV-1 genome including *gag*, *pol* and the long terminal repeat (LTR) (Beloukas et al., 2009; Kabamba-Mukadi et al., 2005; Rouzioux and Avettand-Fenoël, 2018;

van der Sluis et al., 2013; Vandergeeten et al., 2014; Yun, Fredriksson, and Sonnerborg, 2002). The strength of these assays is the rapid turn-around from sample collection to DNA quantification and the possibility to identify different HIV-1 DNA forms, such as integrated DNA, unintegrated linear DNA forms and 2-LTR circular DNA (De Spiegelaere et al., 2014; Kostrikis et al., 2002; Sharkey et al., 2000; van der Sluis et al., 2013; Vandergeeten et al., 2014). These different HIV-1 DNA forms have been used as markers of HIV-1 persistence in a number of different studies, reviewed here (Ruggiero et al., 2017). 2-LTR circular DNA is a product of abortive integration, and while some studies have suggested they are stable in CD4+ cells (Pace, Graf, and O'Doherty, 2013), they are considered markers of recent infection and ongoing replication notwithstanding therapy (Chun et al., 1997b; Koelsch et al., 2008; Murray et al., 2012; Sharkey et al., 2011; Zhu et al., 2011). Only assays targeting the viral LTR allow for the discrimination of different HIV-1 forms in addition to the fact that the LTR contains some of the most conserved regions of the viral genome (van der Sluis et al., 2013).

We have comprehensively analysed two HIV-1 DNA quantification assays, herein referred to as Vandergeetan, (CV) (Vandergeeten et al., 2014) and van der Sluis (RvS) (van der Sluis et al., 2013), both of which target highly conserved regions in the LTR region of the virus genome (van der Sluis et al., 2013; Vandergeeten et al., 2014) (Fig. 1). Both assays utilise a PCR pre-amplification step with primers designed to amplify all forms of HIV-1 DNA (total HIV-1 DNA) that have been fully reverse transcribed, including linear integrated, linear unintegrated and circular DNA forms, while excluding the short abortive transcripts.

However, both assays are able to distinguish between total HIV-1 DNA and 2-LTR circular DNA with the use of alternative primer sets in the pre-amplification step. The CV assay is also able to distinguish integrated HIV-1 DNA via the use of primers targeting human *Alu*

sequences, randomly dispersed in the human genome (Ruggiero et al., 2017; Vandergeeten et al., 2014). A prominent HIV-1 LTR based DNA assay, herein referred to as Rouzioux (CRx), was excluded from this comparison because this assay does not distinguish between different DNA types (Rouzioux, Melard, and Avettand-Fenoel, 2014). Furthermore, we have evaluated several calibration cell-lines, aiming to establish a stable and reproducible source of HIV-1 DNA for use as a standard curve. Additionally, we have analysed the primer sequences and used this information to establish an assay that would predict a broader specificity and increased sensitivity.

2. Materials and Methods

2.1. Cell Lines and Calibration Standards. HIV-1 quantification standards were produced from cell lines including 8E5 (CFAR 95), ACH-2 (CFAR 349) and J-Lat 10.6 (CFAR 9849), obtained from the NIH AIDS reagent program. Additionally, we utilised SupT1-14, a previously characterised cell line containing 14 HIV-1 copies per cell in comparing the assays (van der Sluis et al., 2013). Standards for the quantification of cell input were produced from dilutions of DNA derived from HEK293T cells (ATCC CRL-3216). ACH-2, 8E5 and J-Lat 10.6 were maintained in RPMI-1640 medium (Fisher, 11875093) supplemented with 10% heat inactivated FBS (Sigma, non-US origin, F7524) and 1% pen-strep (Fisher, 15140122) at 37 °C with 5% CO₂. HEK293T cells were maintained under the same conditions with advanced DMEM (Fisher, 12491015) used for culturing. Cells were passaged to a maximum of 10 cycles prior to DNA extraction using QIAamp DNA Blood Mini Kit, according to the manufacturer's instructions (Qiagen, 51104). DNA concentration and purity was assessed by Nanodrop analysis (Thermo Scientific, ND-200). The total number of cells and HIV-1 copy

numbers were quantified using the CD3 and LTR quantification assays, respectively, and as previously described (van der Sluis et al., 2013; Vandergeeten et al., 2014). Standards were produced via a dilution series over a range of 5 logs. HIV-1 DNA standards were spiked with uninfected human genomic DNA to equalise DNA input in lower copy numbers.

2.2. Study Population Clinical Sample Preparation. The present study was approved by the Institutional Review Board of the Centre Hospitalier Universitaire Vaudois and all subjects provided written informed consent. CD4⁺ cells were isolated from PBMCs by negative selection using paramagnetic beads (StemCell Technologies) according to supplier's protocol. Purified CD4⁺ cells were digested via incubation with 0.1 mg/ml recombinant proteinase K (Roche, RPROTK-RO) in 10 nM Tris (pH 8.3) for 2 h at 56 °C. Lysate was centrifuged and supernatant recovered and used as input in the HIV-1 quantification assays. Proteinase K lysates were stored at -80 °C until use.

2.3. HIV-1 DNA Quantification Assays. Total HIV-1 DNA was quantified using both CV (Vandergeeten et al., 2014) and RvS (van der Sluis et al., 2013) LTR based HIV-1 DNA as well as CD3 cell quantification assays. Primers and probes used in HIV-1 and CD3 DNA quantification are as described previously (van der Sluis et al., 2013; Vandergeeten et al., 2014). Additionally, a commercial cell quantification kit targeting the β -actin gene was used (ABI Applied Biosystems TaqMan β -actin Detection Reagent, 401846). Pre-amplifications were performed in 25 μ l reactions using Taq polymerase (Invitrogen, 10342020), as previously described (van der Sluis et al., 2013; Vandergeeten et al., 2014). Quantifications were performed in 20 μ l reactions using Supermix-UDG (Invitrogen, 11730025) with the

Qiagen Rotor Gene RotorQ, as described previously (van der Sluis et al., 2013; Vandergeeten et al., 2014). β -actin quantifications were performed according to the manufacturer's instructions. Reagent mixes for the quantification and pre-amplification PCR steps were adapted to the volumes used in this study, though the final concentrations remained the same as previously described (van der Sluis et al., 2013; Vandergeeten et al., 2014).

2.4. Sanger DNA Sequencing. To sequence the primer and probe binding regions of both assays primers were designed in house to amplify the LTR region of patient samples (Table 1). Nested PCR was performed under the following conditions: 2 min (95 °C) followed by 35 cycles of 30 s (95 °C), 30 s (55 °C) and 1 min (72 °C) with a final elongation of 10 min (75 °C). The product of PCR 1 was diluted 1/10 in molecular grade water and this dilution was subsequently used as input for PCR 2. Amplification was analysed using gel electrophoresis and further purified using a Qiagen PCR Purification Kit (28104) prior to sequencing (GATC Biotech and Source Bioscience). Patient sequences were then aligned to primer and probe sequences using BioEdit software to identify mismatches. Following this, new primers were selected to exactly match the patient sample LTR region and used to quantify the total HIV-1 DNA using both assays, as described above (Table 1).

3. Results

3.1. Validation of assay quantification standards. Our aim was to examine the performance of the two assays CV and RvS and using the vast amount of sequence information available to date develop a new assay that will perform most optimally with the highest specificity and sensitivity. The incentive for this consideration was that both HIV-1 DNA quantification

assays target the LTR of the HIV-1 genome, well established as the most conserved region of the genome, and furthermore both utilise a pre-amplification step allowing for the separate quantification of different viral life-cycle stages. In order to do so we initially aimed to define the cell quantification standard using a human genomic DNA input based on 293T cells. We quantified the cell number using two methods; a commercial assay with primers targeting the human β -actin gene and a previously described assay targeting the human CD3 gene (Vandergeeten et al., 2014). We tested a 5 log standard range (10^5 to 10^1 cell equivalents) using both assays and found that they were within the optimum range of amplification efficiency (90-110%) and that there was no significant difference between either over 3 runs ($P=0.8538$) (Fig. 2A and 2B). Based on this result we selected the CD3 quantification assay because it includes a pre-amplification step consistent with the HIV-1 DNA assays.

Further, we ran the two HIV-1 quantifications assays, RvS (van der Sluis et al., 2013) and CV (Vandergeeten et al., 2014), using 5-log serial dilutions (10^5 to 10^1 HIV-1 copies per input) of the J-Lat 10.6, 8E5, SupT-14 and ACH2 cell lines. We found no significant difference between qPCR efficiency of both assays over 6 runs ($P=0.0552$). We next compared the HIV-1 DNA content in these cell lines, aiming to determine the most appropriate cell line for use as a quantification standard.

3.2 Evaluation of calibration cell lines. We evaluated HIV-1 integration model cell lines including ACH2, 8E5 and J-Lat as well as in 'in house' cell line, SupT-14, for their use as calibration standards. Cell lines were grown to 10 passages and the total HIV-1 per 10^6 cells was quantified following DNA extraction. Consistent with recent publications, we showed that HIV-1 copies per cell decreased in 8E5 cells from 1 to 0.2 copies (Fig. 3). Additionally, HIV-1 copies in ACH2 cells were found to increase from 1 to 4 copies per cell. On the

contrary, HIV-1 DNA content was stable in both J-Lat 10.6 and SupT1-14, which contain 1 copy per cell consistent with recent studies (Sunshine et al., 2016) and 14 copies per cell as demonstrated previously (van der Sluis et al., 2013), respectively (Fig. 3). Based on these findings we used the J-Lat 10.6 to quantify patient samples in this study.

3.3 HIV-1 quantification in patient samples. We then compared the two HIV-1 DNA quantification assays using patient samples. Overall, a strong correlation was found between the results produced with the RvS and CV assays ($r=0.9759$, $P<0.0001$) (Fig. 4C). Nonetheless, the mean quantification of patient samples was significantly higher when using the RvS (3.385 Log₁₀ HIV-1 copies/106 cells) HIV-1 assay compared to the CV assay (3.203 Log₁₀ HIV-1 copies/106) ($P=0.0021$) suggesting a slight advantage of RvS over CV when testing patient material (Fig. 4B). A possible explanation would be that the CV amplified product is longer than the RvS thus affecting the amplification efficiency. Furthermore, the implementation of software (<http://unafold.rna.albany.edu>) revealing folded structures indicated that more complex folded structures of the CV amplicon could also account for lower amplification efficiency. (Fig. 5) Of note, in 4/38 (10.52 %) of patients we observed significant differences in quantification between the two assays (114: $P=0.00101$, 72: $P>0.0001$, 23: $P>0.0001$, 111: $P=0.0003$) (Fig. 4A).

We next aimed to test the performance of the two assays when HIV-1 copy input was diluted to 10 copies. We found that in low copies, correlation was skewed towards the CV assay ($r=0.8220$, $P<0.0001$) and that in 9/25 (36%) of samples quantification was significantly different between the assays (Fig. 4D and 4F). However, there was no significant difference between the mean quantification of low copy patient samples ($P=0.1456$) (Fig. 4E).

3.4 HIV-1 quantification using patient tailored primers. We showed that both assays performed comparably; however, there was discrepancy in quantification observed with some patient samples. We aimed to elucidate the cause of this discrepancy by sequencing the LTR of patient samples. Two forward and reverse primers were selected for nested LTR amplification based on identity with sequences of the Los Alamos database (Table 1). The LTR of patient samples was subsequently sequenced with the Sanger platform. Patient sequences were analysed using BioEdit and sequences were manually aligned to primer and probes used in both assays (data not shown). Based on this alignment, we selected primers tailored to patient samples (Table 1). Patient samples were quantified simultaneously with the universal and the patient tailored primers. For each patient sample tested, the quantification with patient tailored primers was significantly higher than when the universal primer was used (RvS 132 $p=0.0056$, RvS 108 $p=0.0083$, RvS 124 $p=0.0010$, CV 132 $p=0.0004$, CV 124 $p=0.0008$, CV 132 $p=0.0077$) (Fig. 6A and 6B). Together, this is a 131.9% and 141.6% average increase for RvS and CV assays, respectively, when patient tailored primers were utilised, demonstrating that sequence diversity can occasionally impair the accuracy of the assay.

We subsequently interrogated the sequence information available 'to date' at the Los Alamos HIV-1 database. Our *in silico* analysis revealed that the oligonucleotide with the higher propensity for mismatches was the RvS forward pre-amplification primer, at the 5' end (Fig. 7E), when compared to the other assay primers (Fig. 7A-D). We therefore redesigned this primer in two different versions (RvS-A and RvS-B, Table 1) (Fig. 7F), to compensate the sequence diversity and circumvent 5' end mismatches that would be the most deleterious. These two primer versions were used at equal ratio for the pre-

amplification step. Our results indicate that the new primers, RvS-A and RvS-B used in equal ratio, yield a significantly higher quantification than the existing primer, and this represents an improvement on the assay ($P=0.0057$) (Fig. 8). Though this difference is small, our analysis suggests this primer combination will reduce the risk of mismatching in the 5' end of the primer and increase the overall coverage and accuracy of the assay. As it stands the *in silico* analysis showed that the overall primer diversity ranged between 0.04% and 0.07% as estimated using the neighbour-joining method and the Kimura-2-parameter model (data not shown) suggesting that the RvS-A and B primer combination will rarely underestimate the total DNA load.

4. Discussion

Clinical trials assessing the efficacy of therapeutic vaccination or HIV-1 eradication strategies must utilise robust and reproducible HIV-1 DNA quantification assays. The lack of a standard quantification assay to measure total HIV-1 DNA has led to the development of a number of 'in-house' assays targeting different genomic regions for quantification, but this variation may render the results of different clinical trials incomparable. We selected two HIV-1 quantification assays, CV (Vandergeeten et al., 2014) and RvS (van der Sluis et al., 2013), for comprehensive evaluation to determine if results obtained were comparable and the assays could therefore be used interchangeably. These assays were selected for the ability to distinguish different HIV-1 DNA forms, including 2-LTR circular DNA, which can serve as a marker of recent infection and therefore be used to determine the success of treatment. The differential quantification of different DNA markers is facilitated by the use

of a pre-amplification step and primers targeting the conserved regions of the LTR of the viral genome.

Recent data has suggested that 8E5, a commonly used latency model containing one copy of HIV-1 per cell, is unstable and rapidly loses HIV-1 copies during passaging (Busby et al., 2017; Wilburn et al., 2016). Further, a study has shown evidence of ongoing replication within ACH2 cells during passaging, resulting in an increase in HIV-1 copies per cell (Sunshine et al., 2016). This study has proposed the use of J-Lat cells as quantification standards as these contain a non-replication competent copy of HIV-1 that remains stable after a number of passages (Sunshine et al., 2016). Consistent with these findings, we have compared a number of well characterised calibration cell lines and discovered that 8E5 and ACH2 cells are unsuitable for use due to the change in HIV-1 DNA copies during passaging (Busby et al., 2017; Wilburn et al., 2016). Further, we have demonstrated that J-Lat cells contain ~ 1 copy per cell and would therefore be the most suitable for use in DNA quantification studies. The universal use of only one cell line as a calibration standard would reduce variability of different HIV-1 DNA assays and across different labs, rendering data obtained from studies and clinical trials more comparable. Further, we demonstrate that both LTR based assays amplify well-characterised HIV-1 calibration cell lines with equal efficiency, removing the potential of bias in quantification of patient samples arising from a bias in the amplification of the standard curve.

Our data indicate that both assays perform comparably when quantifying total HIV-1 DNA in patient samples as well as cell lines and that these quantifications correlate strongly. Despite this, we have shown that the RvS assay quantifies the patient set as a whole, 0.2 Log₁₀ HIV-1 copies higher than the CV assay, suggesting that the quantification of patient samples is more efficient when using this assay. When these samples were diluted to ~ 10

copies per input the strength of the correlation of the assays was lost. This is due to inherently higher variation in the quantification of low copy samples, owing to the stochastic distribution of template within the sample. However, the assay was improved when primers were redesigned using sequences derived from a recent HIV-1 database.

The RvS and CV assays have the ability to only quantify HIV-1 DNA that has undergone full reverse transcription as both implement a pre-amplification step that utilises primers strategically placed to bind DNA only present following first and second strand transfer (Fig. 1). However, the RvS assay performed slightly better, possibly due to the smaller amplicon size. Based on that observation we improved the performance and accuracy of the RvS assay by undergoing an in-silico analysis of the primer sequences using all available HIV-1 sequences from the Los Alamos database. The high degree of HIV-1 sequence heterogeneity means that sequence variation will be encountered even within the most conserved regions of the genome. Our analysis showed that the forward pre-amplification primer was most divergent from published sequences and we therefore redesigned this primer and suggest that two primers (Table 1) should be used to improve the accuracy and sensitivity of this assay.

HIV-1 DNA quantification is an essential tool for monitoring HIV-1 vaccine and therapy trials due to its low cost, fast turnaround time and high throughput capacity. Notwithstanding its advantages, DNA based assays cannot distinguish between replication competent and replication defective pro-virus, and will therefore overestimate the size of the replication competent LR (Rouzioux and Avettand-Fenoël, 2018; Ruggiero et al., 2017). Despite this, recent studies have suggested defective pro-virus contributes to HIV-1 pathogenesis, and so measuring the size of all pro-virus present in a sample is useful marker of vaccine or treatment success and projection for disease progression (Rouzioux and

Avettand-Fenoël, 2018; Ruggiero et al., 2017). In any case these described assays are a cheaper, faster and more practical alternative to the cell based viral outgrowth assay (VOA) which is able to specifically quantify only replication competent pro-virus by measuring virus production in PBMCs following activation (Rouzioux and Avettand-Fenoël, 2018). Here we demonstrate that whilst two HIV-1 quantification assays perform comparably we have improved the RvS assay through increasing the coverage of the diverse HIV-1 populations that can be detected with the assay.

Summary

Currently there is no standard HIV-1 DNA quantification assay for use in clinical trials and a comparison of HIV-1 assays has not been performed. Here, we evaluate two HIV-1 DNA quantification assays for their ability to accurately quantify HIV-1 DNA load in patient samples. Additionally, we have compared a number of commonly used HIV-1 latency cells for their use as HIV-1 quantification standards. We have shown that the two assays perform comparably and correlate strongly, however, one assay performs significantly better and this assay was chosen for improvement. We have also shown that J-Lat are the most suitable HIV-1 quantification standard owing to the stability of the integrated viral genome. We have redesigned primers based on analyses of the HIV-1 database to update and improve the HIV-1 quantification assay.

Acknowledgements

We are indebted to the patients in the study for providing materials. This study was funded under a European Union's Horizon 2020 Research and Innovation Programme under the grant agreement no. 681032, "European HIV Vaccine Alliance" (EHVA).

References

- Archin, N.M., Kirchherr, J.L., Sung, J.A.M., Clutton, G., Sholtis, K., Xu, Y., Allard, B., Stuelke, E., Kashuba, A.D., Kuruc, J.D., Eron, J., Gay, C.L., Goonetilleke, N. and Margolis, D.M., 2017. Interval dosing with the HDAC inhibitor vorinostat effectively reverses HIV latency. *The Journal of Clinical Investigation* 127, 3126-3135.
- Archin, N.M., Liberty, A.L., Kashuba, A.D., Choudhary, S.K., Kuruc, J.D., Crooks, A.M., Parker, D.C., Anderson, E.M., Kearney, M.F., Strain, M.C., Richman, D.D., Hudgens, M.G., Bosch, R.J., Coffin, J.M., Eron, J.J., Hazuda, D.J. and Margolis, D.M., 2012. Administration of vorinostat disrupts HIV-1 latency in patients on antiretroviral therapy. *Nature* 487, 482.
- Barouch, D.H., Whitney, J.B., Moldt, B., Klein, F., Oliveira, T.Y., Liu, J., Stephenson, K.E., Chang, H.-W., Shekhar, K., Gupta, S., Nkolola, J.P., Seaman, M.S., Smith, K.M., Borducchi, E.N., Cabral, C., Smith, J.Y., Blackmore, S., Sanisetty, S., Perry, J.R., Beck, M., Lewis, M.G., Rinaldi, W., Chakraborty, A.K., Poignard, P., Nussenzweig, M.C. and Burton, D.R., 2013. Therapeutic efficacy of potent neutralizing HIV-1-specific monoclonal antibodies in SHIV-infected rhesus monkeys. *Nature* 503, 224-228.
- Beloukas, A., Paraskevis, D., Haida, C., Sypsa, V. and Hatzakis, A., 2009. Development and assessment of a multiplex real-time PCR assay for quantification of human immunodeficiency virus type 1 DNA. *Journal of clinical microbiology* 47, 2194-9.
- Brechtel, J.R., Breitbart, W., Galietta, M., Krivo, S. and Rosenfeld, B., 2001. The use of highly active antiretroviral therapy (HAART) in patients with advanced HIV infection: impact on medical,

- palliative care, and quality of life outcomes. *Journal of pain and symptom management* 21, 41-51.
- Busby, E., Whale, A.S., Ferns, R.B., Grant, P.R., Morley, G., Campbell, J., Foy, C.A., Nastouli, E., Huggett, J.F. and Garson, J.A., 2017. Instability of 8E5 calibration standard revealed by digital PCR risks inaccurate quantification of HIV DNA in clinical samples by qPCR. *Scientific Reports* 7, 1209.
- Chun, T.-W., Stuyver, L., Mizell, S.B., Ehler, L.A., Mican, J.A.M., Baseler, M., Lloyd, A.L., Nowak, M.A. and Fauci, A.S., 1997a. Presence of an inducible HIV-1 latent reservoir during highly active antiretroviral therapy. *Proceedings of the National Academy of Sciences* 94, 13193-13197.
- Chun, T.W., Carruth, L., Finzi, D., Shen, X., DiGiuseppe, J.A., Taylor, H., Hermankova, M., Chadwick, K., Margolick, J., Quinn, T.C., Kuo, Y.H., Brookmeyer, R., Zeiger, M.A., Barditch-Crovo, P. and Siliciano, R.F., 1997b. Quantification of latent tissue reservoirs and total body viral load in HIV-1 infection. *Nature* 387, 183-8.
- Davey, R.T., Bhat, N., Yoder, C., Chun, T.-W., Metcalf, J.A., Dewar, R., Natarajan, V., Lempicki, R.A., Adelsberger, J.W., Miller, K.D., Kovacs, J.A., Polis, M.A., Walker, R.E., Falloon, J., Masur, H., Gee, D., Baseler, M., Dimitrov, D.S., Fauci, A.S. and Lane, H.C., 1999. HIV-1 and T cell dynamics after interruption of highly active antiretroviral therapy (HAART) in patients with a history of sustained viral suppression. *Proceedings of the National Academy of Sciences* 96, 15109-15114.
- De Rose, R., Fernandez, C.S., Smith, M.Z., Batten, C.J., Alcântara, S., Peut, V., Rollman, E., Loh, L., Mason, R.D., Wilson, K., Law, M.G., Handley, A.J. and Kent, S.J., 2008. Control of Viremia and Prevention of AIDS following Immunotherapy of SIV-Infected Macaques with Peptide-Pulsed Blood. *PLoS pathogens* 4, e1000055.
- De Spiegelaere, W., Malatinkova, E., Lynch, L., Van Nieuwerburgh, F., Messiaen, P., O'Doherty, U. and Vandekerckhove, L., 2014. Quantification of integrated HIV DNA by repetitive-sampling Alu-HIV PCR on the basis of poisson statistics. *Clinical chemistry* 60, 886-95.

- Elliott, J.H., McMahon, J.H., Chang, C.C., Lee, S.A., Hartogensis, W., Bumpus, N., Savic, R., Roney, J., Hoh, R., Solomon, A., Piatak, M., Gorelick, R.J., Lifson, J., Bacchetti, P., Deeks, S.G. and Lewin, S.R., 2015. Short-term administration of disulfiram for reversal of latent HIV infection: a phase 2 dose-escalation study. *The Lancet HIV* 2, e520-e529.
- Finzi, D., Hermankova, M., Pierson, T., Carruth, L.M., Buck, C., Chaisson, R.E., Quinn, T.C., Chadwick, K., Margolick, J., Brookmeyer, R., Gallant, J., Markowitz, M., Ho, D.D., Richman, D.D. and Siliciano, R.F., 1997. Identification of a Reservoir for HIV-1 in Patients on Highly Active Antiretroviral Therapy. *Science* 278, 1295-1300.
- Fuller, D.H., Rajakumar, P., Che, J.W., Narendran, A., Nyaundi, J., Michael, H., Yager, E.J., Stagnar, C., Wahlberg, B., Taber, R., Haynes, J.R., Cook, F.C., Ertl, P., Tite, J., Amedee, A.M. and Murphey-Corb, M., 2012. Therapeutic DNA Vaccine Induces Broad T Cell Responses in the Gut and Sustained Protection from Viral Rebound and AIDS in SIV-Infected Rhesus Macaques. *PLOS ONE* 7, e33715.
- Fuller, D.H., Rajakumar, P.A., Wu, M.S., McMahon, C.W., Shipley, T., Fuller, J.T., Bazmi, A., Trichel, A.M., Allen, T.M., Mothe, B., Haynes, J.R., Watkins, D.I. and Murphey-Corb, M., 2006. DNA immunization in combination with effective antiretroviral drug therapy controls viral rebound and prevents simian AIDS after treatment is discontinued. *Virology* 348, 200-215.
- Garcia, F., Climent, N., Guardo, A.C., Gil, C., Leon, A., Autran, B., Lifson, J.D., Martinez-Picado, J., Dalmau, J., Clotet, B., Gatell, J.M., Plana, M. and Gallart, T., 2013. A dendritic cell-based vaccine elicits T cell responses associated with control of HIV-1 replication. *Science translational medicine* 5, 166ra2.
- Hel, Z., Nacsa, J., Trynieszewska, E., Tsai, W.-P., Parks, R.W., Montefiori, D.C., Felber, B.K., Tartaglia, J., Pavlakis, G.N. and Franchini, G., 2002. Containment of Simian Immunodeficiency Virus Infection in Vaccinated Macaques: Correlation with the Magnitude of Virus-Specific Pre- and Postchallenge CD4+ and CD8+ T Cell Responses. *The Journal of Immunology* 169, 4778-4787.

- Hel, Z., Venzon, D., Poudyal, M., Tsai, W.P., Giuliani, L., Woodward, R., Chougnet, C., Shearer, G., Altman, J.D., Watkins, D., Bischofberger, N., Abimiku, A., Markham, P., Tartaglia, J. and Franchini, G., 2000. Viremia control following antiretroviral treatment and therapeutic immunization during primary SIV251 infection of macaques. *Nature medicine* 6, 1140-6.
- Joos, B., Fischer, M., Kuster, H., Pillai, S.K., Wong, J.K., Böni, J., Hirschel, B., Weber, R., Trkola, A., Günthard, H.F. and Study, T.S.H.C., 2008. HIV rebounds from latently infected cells, rather than from continuing low-level replication. *Proceedings of the National Academy of Sciences* 105, 16725-16730.
- Kabamba-Mukadi, B., Henrivaux, P., Ruelle, J., Delferriere, N., Bodeus, M. and Goubau, P., 2005. Human immunodeficiency virus type 1 (HIV-1) proviral DNA load in purified CD4+ cells by LightCycler real-time PCR. *BMC infectious diseases* 5, 15.
- Kim, Y., Anderson, J.L. and Lewin, S.R., 2018. Getting the "Kill" into "Shock and Kill": Strategies to Eliminate Latent HIV. *Cell Host & Microbe* 23, 14-26.
- Koelsch, K.K., Liu, L., Haubrich, R., May, S., Havlir, D., Günthard, H.F., Ignacio, C.C., Campos-Soto, P., Little, S.J., Shafer, R., Robbins, G.K., D'Aquila, R.T., Kawano, Y., Young, K., Dao, P., Spina, C.A., Richman, D.D. and Wong, J.K., 2008. Dynamics of total, linear nonintegrated, and integrated HIV-1 DNA in vivo and in vitro. *J Infect Dis* 197, 411-9.
- Kostrikis, L.G., Touloumi, G., Karanicolos, R., Pantazis, N., Anastassopoulou, C., Karafoulidou, A., Goedert, J.J., Hatzakis, A. and for the Multicenter Hemophilia Cohort Study, G., 2002. Quantitation of Human Immunodeficiency Virus Type 1 DNA Forms with the Second Template Switch in Peripheral Blood Cells Predicts Disease Progression Independently of Plasma RNA Load. *Journal of virology* 76, 10099-10108.
- Lévy, Y., Thiébaud, R., Montes, M., Lacabaratz, C., Sloan, L., King, B., Pérusat, S., Harrod, C., Cobb, A., Roberts, L.K., Surenaud, M., Boucherie, C., Zurawski, S., Delaugerre, C., Richert, L., Chêne, G., Banchereau, J. and Palucka, K., 2014. Dendritic cell-based therapeutic vaccine elicits

- polyfunctional HIV-specific T-cell immunity associated with control of viral load. *European Journal of Immunology* 44, 2802-2810.
- Lu, W., Arraes, L.C., Ferreira, W.T. and Andrieu, J.M., 2004. Therapeutic dendritic-cell vaccine for chronic HIV-1 infection. *Nature medicine* 10, 1359-65.
- Lu, W., Wu, X., Lu, Y., Guo, W. and Andrieu, J.M., 2003. Therapeutic dendritic-cell vaccine for simian AIDS. *Nature medicine* 9, 27-32.
- Margolis, D.M., Garcia, J.V., Hazuda, D.J. and Haynes, B.F., 2016. Latency reversal and viral clearance to cure HIV-1. *Science* 353.
- Murray, J.M., McBride, K., Boesecke, C., Bailey, M., Amin, J., Suzuki, K., Baker, D., Zaunders, J.J., Emery, S., Cooper, D.A., Koelsch, K.K. and Kelleher, A.D., 2012. Integrated HIV DNA accumulates prior to treatment while episomal HIV DNA records ongoing transmission afterwards. *AIDS (London, England)* 26, 543-50.
- Mylvaganam, G.H., Silvestri, G. and Amara, R.R., 2015. HIV therapeutic vaccines: moving towards a functional cure. *Current Opinion in Immunology* 35, 1-8.
- Pace, M.J., Graf, E.H. and O'Doherty, U., 2013. HIV 2-long terminal repeat circular DNA is stable in primary CD4+T Cells. *Virology* 441, 18-21.
- Rothenberger, M.K., Keele, B.F., Wietgrefe, S.W., Fletcher, C.V., Beilman, G.J., Chipman, J.G., Khoruts, A., Estes, J.D., Anderson, J., Callisto, S.P., Schmidt, T.E., Thorkelson, A., Reilly, C., Perkey, K., Reimann, T.G., Utay, N.S., Nganou Makamdop, K., Stevenson, M., Douek, D.C., Haase, A.T. and Schacker, T.W., 2015. Large number of rebounding/founder HIV variants emerge from multifocal infection in lymphatic tissues after treatment interruption. *Proceedings of the National Academy of Sciences* 112, E1126-E1134.
- Rouzioux, C. and Avettand-Fenoël, V., 2018. Total HIV DNA: a global marker of HIV persistence. *Retrovirology* 15, 30.

- Rouzioux, C., Melard, A. and Avettand-Fenoel, V., 2014. Quantification of total HIV1-DNA in peripheral blood mononuclear cells. *Methods in molecular biology* (Clifton, N.J.) 1087, 261-70.
- Ruggiero, A., Malatinkova, E., Rutsaert, S., Paxton, W.A., Vandekerckhove, L. and Spiegelaere, W.D., 2017. Utility of integrated HIV-1 DNA quantification in cure studies. *Future Virology* 12, 215-225.
- Sharkey, M., Babic, D.Z., Greenough, T., Gulick, R., Kuritzkes, D.R. and Stevenson, M., 2011. Episomal Viral cDNAs Identify a Reservoir That Fuels Viral Rebound after Treatment Interruption and That Contributes to Treatment Failure. *PLoS pathogens* 7, e1001303.
- Sharkey, M.E., Teo, I., Greenough, T., Sharova, N., Luzuriaga, K., Sullivan, J.L., Bucy, R.P., Kostrikis, L.G., Haase, A., Veryard, C., Davaro, R.E., Cheeseman, S.H., Daly, J.S., Bova, C., Ellison, R.T., 3rd, Mady, B., Lai, K.K., Moyle, G., Nelson, M., Gazzard, B., Shaunak, S. and Stevenson, M., 2000. Persistence of episomal HIV-1 infection intermediates in patients on highly active anti-retroviral therapy. *Nature medicine* 6, 76-81.
- Sunshine, S., Kirchner, R., Amr, S.S., Mansur, L., Shakhbatyan, R., Kim, M., Bosque, A., Siliciano, R.F., Planelles, V., Hofmann, O., Ho Sui, S. and Li, J.Z., 2016. HIV Integration Site Analysis of Cellular Models of HIV Latency with a Probe-Enriched Next-Generation Sequencing Assay. *Journal of virology* 90, 4511-4519.
- Tateishi, H., Monde, K., Anraku, K., Koga, R., Hayashi, Y., Ciftci, H.I., DeMirici, H., Higashi, T., Motoyama, K., Arima, H., Otsuka, M. and Fujita, M., 2017. A clue to unprecedented strategy to HIV eradication: "Lock-in and apoptosis". *Scientific Reports* 7, 8957.
- van der Sluis, R.M., van Montfort, T., Centlivre, M., Schopman, N.C., Cornelissen, M., Sanders, R.W., Berkhout, B., Jeeninga, R.E., Paxton, W.A. and Pollakis, G., 2013. Quantitation of HIV-1 DNA with a sensitive TaqMan assay that has broad subtype specificity. *Journal of virological methods* 187, 94-102.

- Vandergeeten, C., Fromentin, R., Merlini, E., Lawani, M.B., DaFonseca, S., Bakeman, W., McNulty, A., Ramgopal, M., Michael, N., Kim, J.H., Ananworanich, J. and Chomont, N., 2014. Cross-clade ultrasensitive PCR-based assays to measure HIV persistence in large-cohort studies. *Journal of virology* 88, 12385-96.
- Wilburn, K.M., Mwandumba, H.C., Jambo, K.C., Boliar, S., Solouki, S., Russell, D.G. and Gludish, D.W., 2016. Heterogeneous loss of HIV transcription and proviral DNA from 8E5/LAV lymphoblastic leukemia cells revealed by RNA FISH:FLOW analyses. *Retrovirology* 13, 55.
- Yun, Z., Fredriksson, E. and Sonnerborg, A., 2002. Quantification of human immunodeficiency virus type 1 proviral DNA by the TaqMan real-time PCR assay. *Journal of clinical microbiology* 40, 3883-4.
- Zhu, W., Jiao, Y., Lei, R., Hua, W., Wang, R., Ji, Y., Liu, Z., Wei, F., Zhang, T., Shi, X., Wu, H. and Zhang, L., 2011. Rapid turnover of 2-LTR HIV-1 DNA during early stage of highly active antiretroviral therapy. *PLoS One* 6, e21081.

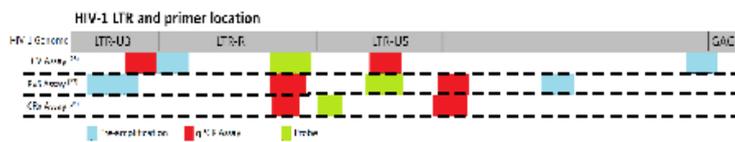


Fig. 1. HIV-1 LTR region: Locations of primers and probes for the CV, RvS and CRx assays. The numbers indicate the position on the HXB2 genome. For CV assay forward quantification primer anneals to Lambda T heel sequence on the forward pre-amplification primer.

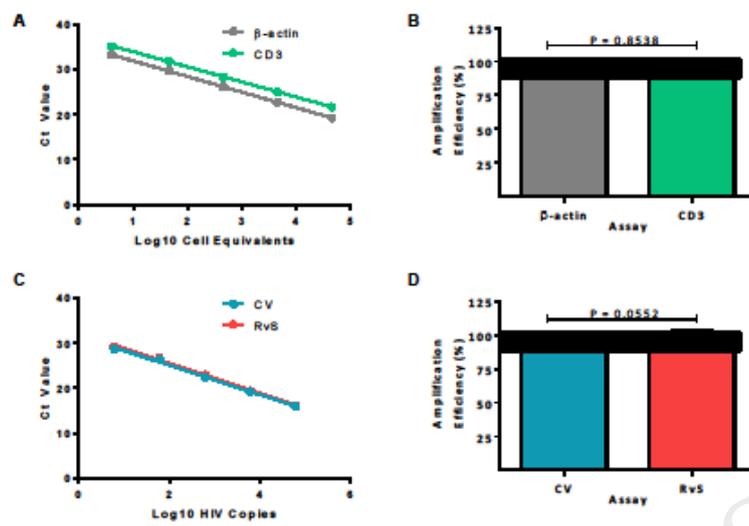


Fig. 1. Comparison of standards and assay performance: A) 5 log serial dilution of human genomic DNA quantified using CD3 and β -actin qPCR. B) Average amplification efficiency of CD3 and β -actin assays (n=3). C) 5 log serial dilution of J-Lat clone 10.6 cells using CV and RvS. D) Average amplification efficiency of CV and RvS assays.

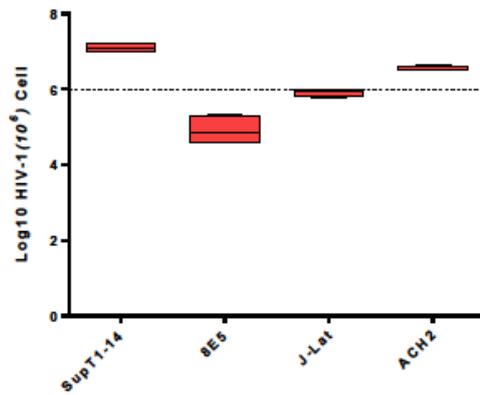


Fig. 3. Quantification using different cell lines: Quantification of three cell lines containing 1 HIV-1 copy per cell (8E5, J-Lat) and 14 HIV-1 copies per cell (SupT1-14). A five log dilution series for each cell line was performed and used as input for the assay. Quantification of each dilution was pooled and standardised to determine the average HIV-1 copies per cell.

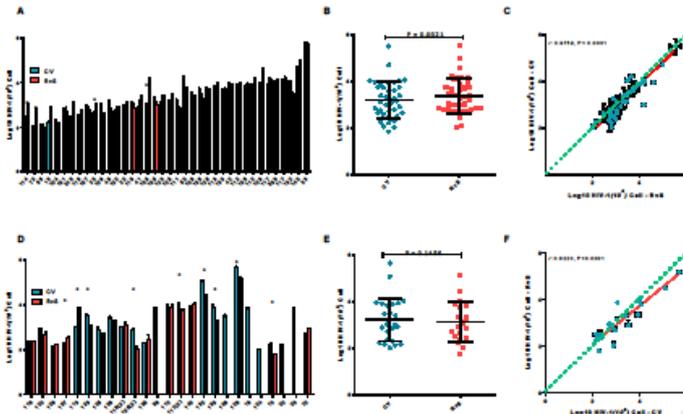


Fig. 4. Quantification of patient samples: A) Pellets of PBMCs or CD4+ cells extracted using proteinase K digestion or Qiagen DNA extraction. Total HIV-1 was quantified using RvS and CV assays and cells were quantified using the CD3 assay. Statistical significance determined using the multiple t-test, Holm-Sidak method, with alpha = 5.000%. B, E) Dot plot showing differences in mean quantification for undiluted and low copy quantification. Significance

determined by paired t-test. D) Samples were diluted to 10 copies per reaction and quantified using both assays. Statistical significance determined using the multiple T test, Holm-Sidak method, with alpha = 5.000%. C, F) Correlation of all samples and correlation of diluted, low copy samples, respectively. Solid red line represents linear regression and green dashed line represents perfect correlation.

ACCEPTED MANUSCRIPT

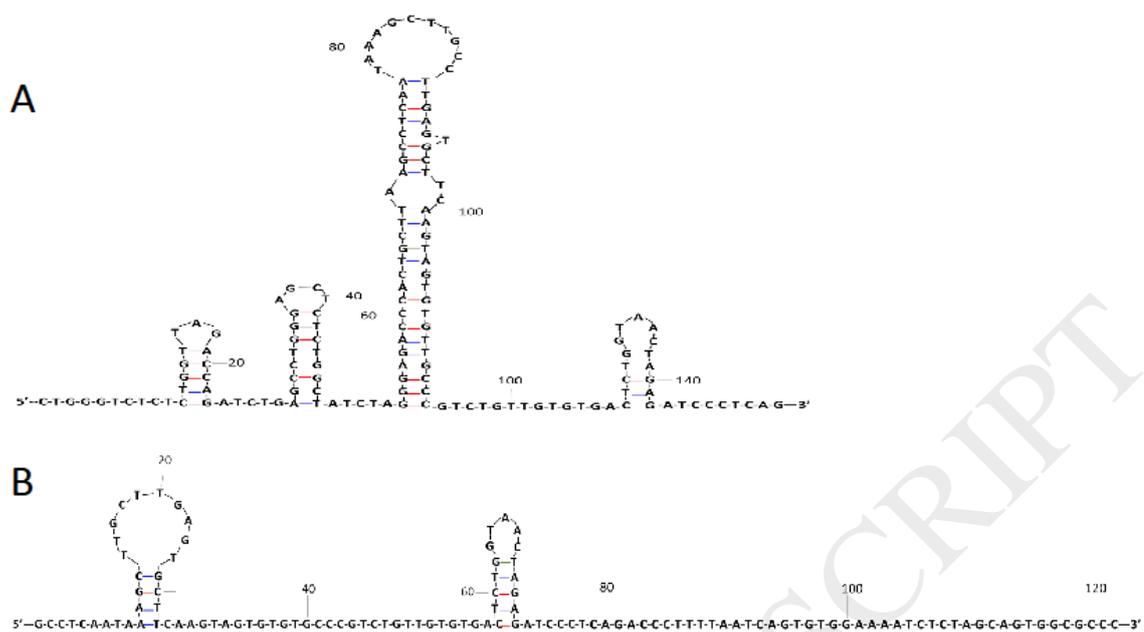


Fig. 5. The probable secondary structure of single stranded HIV-1 DNA produced using the The mfold Web Server (<http://unafold.rna.albany.edu>): A) Depicts the 152 nt CV amplicon (HxB2: 522→643) and B) Depicts the 122 nt RvS amplicon (HxB2: 452→603).

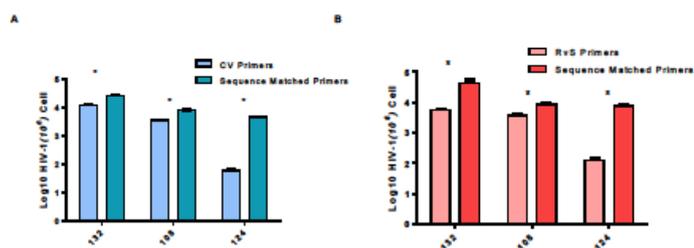


Fig. 6. Quantification with sequence matched primers: Primers designed to match sequences were compared with assay primers: A) Comparison of CV primers to sequence matched primers. B) Comparison of RvS primers to sequence matched primers. Statistical significance determined using the multiple t-test, Holm-Sidak method, with alpha = 5.000%.

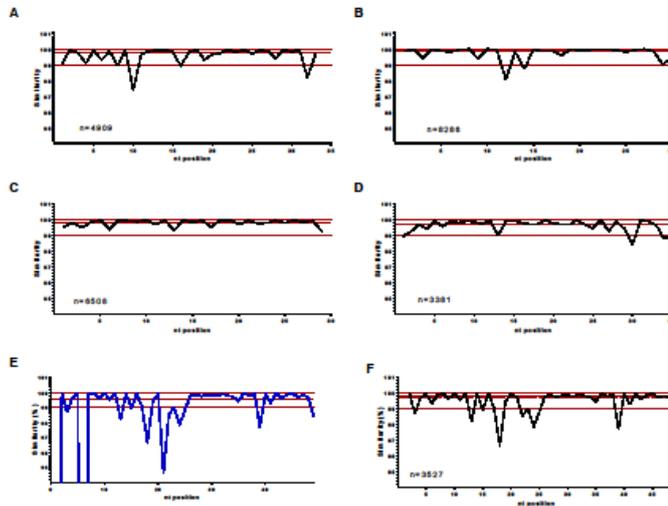


Fig. 7. Analysis of primer and probe sequence identity to published HIV-1 sequences: A) RvS probe sequence B) RvS pre-amplification reverse primer C) RvS qPCR reverse primer D) Region targeted by both VC Probe and RvS qPCR forward primer E) RvS pre-amplification forward primer F) Modified assay primer encompassing both primer A and B, where one has a nucleotide removed (Table 1) n = the number of sequences analysed per oligonucleotide.

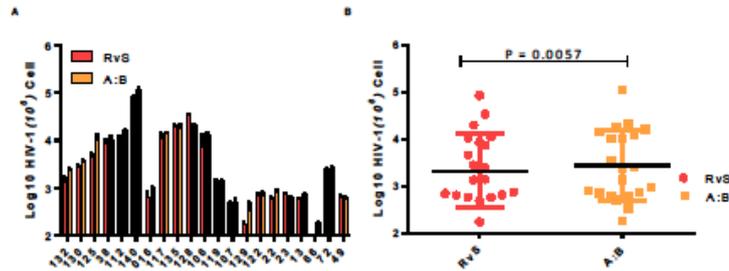


Fig. 8. Comparison of patient sample quantification when using the existing RvS forward primer (red) or a combination of newly designed forward primers, RvS-A and RvS-B (orange) (Table 1). RvS-A and RvS-B primers were used in equal ratio. Significance determined by paired t-test.

TABLE 1 Primers used for the amplification of patient sample LTRs and primers matched to patient sequences. For tailored and redesigned primers nucleotide positions that vary from the universal assay primer are underlined.

<i>Name</i>	<i>Stage</i>	<i>Function</i>	<i>Sequence</i>	<i>Position on HXB2</i>
<i>Seqout-F</i>	Sequencing PCR 1	Forward	CACACACAAGGCTACTTCCCTGATTAGCAGAACT	57-90
<i>Seqout-R</i>	Sequencing PCR1	Reverse	CTTAATACTGACGCTCTCGACCCATCTCTCT	815-784
<i>Seqin-F</i>	Sequencing PCR2	Forward	GGGACTTTCGCTGGGACTTTCC	350-373
<i>Seqin-R</i>	Sequencing PCR2	Reverse	TCTCTCTCCTTAGCCTCCGCTAGTCA	790-763
<i>RvS-preF_132</i>	Pre-amplification	Forward	<u>C</u> AACCTTCAGAA <u>G</u> CTGCATAWAAGCAGCYGCT	409-440
<i>RvS-preR_132</i>	Pre-amplification	Reverse	AGCAAGCCGAGTCT <u>C</u> GCGTC	688-707
<i>RvS-preF_108</i>	Pre-amplification	Forward	<u>G</u> AGCCCGTGGATGCTGCATAWAAGCAGCYGCT	409-440
<i>RvS-preR_108</i>	Pre-amplification	Reverse	AGCA <u>C</u> AGCCGAGTCTGCGTC	688-707
<i>RvS-qF_124</i>	qPCR	Forward	GGGCGCCACTGCTAGAGAA <u>A</u>	625-643
<i>CV-preF_124</i>	Pre-amplification	Forward	ATGCCACGTAAGCGAAACTCTGGGTCTCTDG <u>C</u> T <u>G</u> GAC	452-471
<i>CV-preR_124</i>	Pre-amplification	Reverse	CCATCTCTCTCC <u>T</u> TCTAGC	775-793
<i>CV-preF_132</i>	Pre-amplification	Forward	ATGCCACGTAAGCGAAACTCTGGGTCTCTDG <u>C</u> TAGAC	452-471
<i>CV-preF_108</i>	Pre-amplification	Forward	ATGCCACGTAAGCGAAACTCTGGGTCTCTD <u>G</u> T <u>C</u> AGA	452-471
<i>RvS-preF-A</i>	Pre-amplification	Forward	<u>A</u> RCCCTCAGAH <u>G</u> CTGCATAWAAGCAGCYGCT	410-440
<i>RvS-preF-B</i>	Pre-amplification	Forward	<u>A</u> RCCCTCAGAH <u>G</u> CTGCATAWAAGCAGCYGC	410-439