



LETTER

Reverse Genetic Analysis of Adaptive Mutations within the Capsid Proteins of Enterovirus 71 (EV-A71) Strains Necessary for Infection of CHO-K1 Cells

Carla Bianca Luena Victorio^{1,3} · Yishi Xu¹ · Qimei Ng¹ · Vincent T. K. Chow² · Kaw Bing Chua¹

Received: 20 March 2019 / Accepted: 30 August 2019 / Published online: 21 October 2019
© Wuhan Institute of Virology, CAS 2019

Dear Editor,

Previous studies had described the adaptation of enterovirus 71 (EV-A71) strains that enabled entry and viral replication in Chinese Hamster Ovary (CHO) cell line (Zaini and McMinn 2012; Zaini *et al.* 2012). These adapted strains derived from serial passage of a clinical isolate in CHO cells exhibited an amino acid substitution at VP2₁₄₉, which enhanced viral replication by 100~1000-fold compared to the clinical isolate. The VP2₁₄₉ mutation was claimed responsible for adaptation to CHO-K1 cells without performing detailed molecular analyses to support these claims. In this study, we evaluate various VP1 and VP2 mutations in two CHO-adapted EV-A71 strains derived in our lab to assess their contribution to the phenotype of CHO cell adaptation.

Two EV-A71 strains derived in our laboratory and found to productively infect CHO cells, EV71:TLLm (Genbank accession no. KF514879) and EV71:TLLcho (Genbank accession no. KM508794.1), were evaluated in this study. The adaptation history of EV71:TLLm from the clinical isolate EV71:BS (Genbank accession no. KF514878.1) was described previously (Victorio *et al.*

2014). EV71:TLLcho was derived from serial adaptation of EV71:TLLm in Chinese Hamster Ovary, CHO-K1 cells (ATCC[®] CCL-61) for 20 cycles. To evaluate the infectivity of EV71:TLLm and EV71:TLLcho in CHO-K1 cells, we inoculated the viruses (10 MOI) onto a monkey kidney cell line (Vero; ATCC[®] CCL-81) and CHO-K1 cell line for 1 h at 37 °C, washed twice in PBS, and subsequently incubated in DMEM (1% FBS). At 48 h post-infection, live cell images were taken. Infected cells that have detached from the flask were coated onto Teflon slides (Erie, USA) and processed for immunofluorescent (I.F.) detection of viral antigens using pan-enterovirus monoclonal antibodies (Merck Millipore, USA) as previously described (Victorio *et al.* 2014). Viral titers in infected cell culture supernatants were also measured (Reed and Muench 1938; Victorio *et al.* 2014), and viral growth kinetics in CHO-K1 cells were compared by measuring viral titers at 6, 12, 24, 36, 48, and 54 h post-infection.

All three virus strains—EV71:BS, EV71:TLLm, and EV71:TLLcho—infected Vero cells, which exhibited lytic cell death and expressed viral antigens at 48 h post-infection (Fig. 1A). In contrast, only EV71:TLLcho productively infected CHO-K1 cells, as demonstrated by lytic cell death, viral antigen detection, and high viral titers from infected CHO-K1 cells (Fig. 1A, 1B). EV71:TLLm also infected CHO-K1 cells, although at a much slower replication kinetics and 100-fold lower titers (Fig. 1B) and despite the absence of lytic cell death (Fig. 1A). These findings confirm that EV71:TLLm and EV71:TLLcho strains, in contrast with the clinical isolate EV71:BS, were adapted to infect CHO-K1 cells.

The viral capsid mediates entry into host cells by interacting with specific cell-entry receptors. For EV-A71, the main cell-entry and uncoating receptor is the Scavenger Receptor Class B member 2 (SCARB2) protein (Yamayoshi *et al.* 2009). EV-A71 clinical strains are known to not infect rodent cells, primarily because of the low amino acid sequence similarity between primate and

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s12250-019-00167-4>) contains supplementary material, which is available to authorized users.

✉ Kaw Bing Chua
chuakb@tll.org.sg

¹ Temasek Lifesciences Laboratory, 1 Research Link, National University of Singapore, Singapore 117604, Singapore

² Host and Pathogen Interactivity Laboratory, Department of Microbiology, Yong Loo Lin School of Medicine, National University Health System, National University of Singapore, Singapore 117545, Singapore

³ Present Address: Laboratory for Translational and Molecular Imaging, Cancer and Stem Cell Biology Programme, Duke-NUS Medical School, Singapore 169857, Singapore

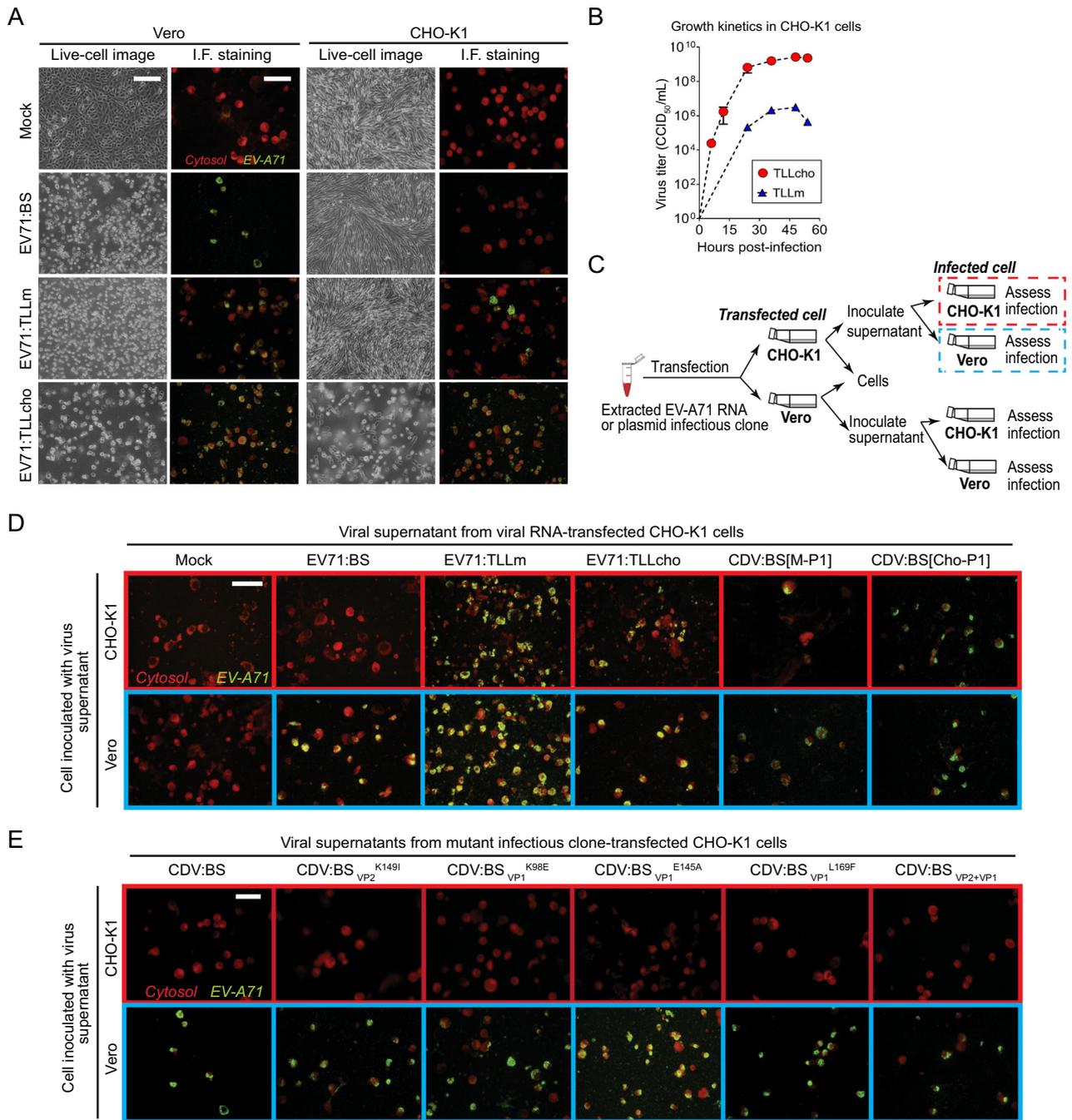


Fig. 1 Evaluation of adaptive capsid mutations in CHO-adapted EV71:TLLm and EV71:TLLcho strains. **(A)** Representative live-cell and immunofluorescence (I.F.) staining images of virus-infected cells. Monkey kidney Vero cells and Chinese hamster ovary CHO-K1 cells inoculated with 10 MOI of either EV71:BS, EV71:TLLm or EV71:TLLcho were imaged at 48 h post-infection. The scale bars represent 50 μ m. **(B)** Viral growth kinetics in CHO-K1 cells determined by measuring viral titers at various time-points post-infection. Titters are expressed as 50% cell-culture infectious dose (CCID₅₀) per ml. **(C)** Schematic of experimental approach for

evaluating the infectivity of extracted viral RNA and plasmid infectious clones. **(D)** Representative images of I.F. staining of CHO-K1 and Vero cells inoculated with transfection supernatants from viral RNA-transfected CHO-K1 cells. **(E)** Representative images of I.F. staining of CHO-K1 and Vero cells inoculated with transfection supernatants from mutant infectious clone-transfected CHO-K1 cells. Cells were stained with pan-enterovirus antibody (green signals) and counter-stained with Evan’s Blue (red background) Scale bars represent 50 μ m.

human SCARB2 proteins (Victorio *et al.* 2016), which result in different conformations (Dang *et al.* 2014). Similarly, the SCARB2 protein expressed by CHO-K1 cells is more similar to mouse than human SCARB2 (Supplementary Figure S1), partly explaining why CHO-K1 cells are naturally resistant to infection with EV-A71 clinical strains.

We evaluated the contribution of the capsid in infecting CHO-K1 cells by transfecting genomic RNA extracted from EV71:TLLm and EV71:TLLcho into CHO-K1 cells. Transfection of viral RNA bypasses receptor-mediated cellular entry and introduces naked RNA directly into the cytoplasm. Subsequently, the resulting supernatant at 48 h post-transfection was re-inoculated onto both Vero and CHO-K1 cells to assess the production of viable infectious virus from transfection (Fig. 1C). Vero and CHO-K1 cells transfected with RNA extracted from either EV71:BS, EV71:TLLm or EV71:TLLcho expressed viral antigens as detected by I.F. staining (Supplementary Figure S2A, S2B). Re-inoculation of transfection supernatants from CHO-K1 cells onto fresh Vero cells also resulted in positive I.F. detection of viral antigens (Fig. 1D). Re-inoculation of the same CHO-K1 transfection supernatants, with

the exception of EV71:BS RNA, onto fresh CHO-K1 cells also resulted in cellular infection (Fig. 1D). We observed similar phenomena when supernatants from viral RNA-transfected Vero cells were passaged onto fresh Vero and CHO-K1 cells (Supplementary Figure S2C). These observations suggest that compared to the capsid protein of EV71:BS, EV71:TLLm and EV71:TLLcho capsids possess adaptive mutations that enable the virus to infect CHO-K1 cells.

To further confirm this finding, we synthesized chimeric EV71:BS infectious clones possessing the entire capsid protein derived from either EV71:TLLm or EV71:TLLcho as previously described (Victorio *et al.* 2016) (See Supplementary Materials for full details). These clones were transfected into Vero and CHO-K1 cells using Lipofectamine 2000 (Invitrogen, USA) to obtain clone-derived viruses (CDV:BS[M-P1] and CDV:BS[Cho-P1]). These chimeric viruses successfully infected CHO-K1 cells upon viral RNA transfection (data not shown). Re-inoculation of supernatants from CHO-K1 cells transfected with either CDV:BS[M-P1] or CDV:BS[Cho-P1] RNA onto fresh CHO-K1 cells also resulted in infection (Fig. 1D), suggesting that the adaptive mutations required for successful

Table 1 Non-synonymous mutations in the capsid region (P1) EV71:TLLcho relative to EV71:BS.

Genome region	Nucleotide changes	Amino acid changes	
		Polyprotein numbering	Mature protein numbering
VP4 (747-953)	A809G	E21G	E21G
VP2 (954-1715)	G1359A	V204I	V135I
	G1385C	S213T	S144T
	A1400T	K218I	K149I
	G1429C	E228P	E159P
	A1430C	E228P	E159P
VP3 (1716-2441)	G1900C	A385P	A62P
	A2287G	T514A	T191A
	A2413T	S556C	S233C
	A2421G	I558M	I235M
	VP1 (2442-3332)	T2462C	V572A
	C2530A	Q595K	Q30K
	A2719G	I658V	I93V
	T2724A	D659E	D94E
	A2734G	K663E	<i>K98E</i>
	A2753G	N669G	N104G
	A2876C	E710A	<i>E145A</i>
	A2943T	E732D	E167D
	C2947T	L734F	<i>L169F</i>
	C3165T	S806L	S241L
	T3175C	Y810H	Y245H
	A3286G	N847D	N282D
	G3319T	A858S	A293S

Amino acid substitutions that fall within the VP1 canyon surrounding Gln-172 are given in italics.

infection of CHO-K1 cells reside in the capsid protein of these CHO-adapted virus strains.

To identify specific capsid mutations crucial to CHO cell adaptation, we performed Sanger sequencing of the EV71:TLLm and EV71:TLLcho genomes (Victorio *et al.* 2014). From the aligned capsid gene sequences, we identified 23 non-synonymous mutations that potentially contributed to the CHO-adapted phenotype (Table 1). These include K₁₄₉ → I and S₁₄₄ → T substitutions located in the EF loop (“puff region”) of VP2, also previously identified as a virus neutralization epitope (Liu *et al.* 2011). This also corresponds to the single amino acid substitution reported between the CHO-adapted strains and parental clinical isolate (Zaini *et al.* 2012). We also observed six substitutions in the surface-exposed loops of VP1, including K₉₈ → E in the BC loop, E₁₄₅ → A in the DE loop, and L₁₆₉ → F near the centre of the capsid canyon. We hypothesized that these surface-exposed residues, particularly those surrounding the capsid canyon (Rossmann 1989; Plevka *et al.* 2014) and interacting with virus receptors on host cells would have the greatest enhancement to cellular entry. To assess the contribution of these mutations in CHO cell adaptation, we constructed infectious clones where the VP2 (K₁₄₉ → I) and VP1 (K₉₈ → E, E₁₄₅ → A, and L₁₆₉ → F) mutations were individually introduced into the genome of EV71:BS. These amino acid substitutions appear to be stable in the genome of EV71:TLLcho from earlier passages (Supplementary Figure S3). However, with the exception of VP2 K₁₄₉, these positions did not show mutations between the CHO-adapted and clinical strains previously reported by the McMinn group (Supplementary Figure S4).

The mutant clone-derived viruses (CDVs) were inoculated onto CHO-K1 and Vero cells to assess cellular entry and infection (Fig. 1C). All evaluated CDVs productively infected Vero cells, but none was able to infect CHO-K1 cells (Fig. 1E). We therefore constructed an infectious clone where all the evaluated mutations in VP2 (K₁₄₉ → I) and VP1 (K₉₈ → E, E₁₄₅ → A, and L₁₆₉ → F) were simultaneously introduced into the EV71:BS genome. This CDV:BS_{VP2+VP1} productively infected Vero cells but not CHO-K1 cells. These observations suggest that the VP2 and VP1 mutations evaluated are not sufficient to enable the EV-A71 clinical isolate (EV71:BS) to infect CHO-K1 cells.

In this study, we described two EV71 strains, EV71:TLLm and EV71:TLLcho, that productively infect CHO-K1 cells. EV71:TLLm was previously derived by adaptation in a mouse cell line (NIH/3T3) and infects a number of primate and rodent cell lines (Victorio *et al.* 2014). EV71:TLLcho is a new strain adapted to CHO-K1 cells and exhibits faster growth kinetics than EV71:TLLm. Compared to other EV-A71 strains derived from EV71:BS

strain (Victorio *et al.* 2014), EV71:TLLcho is unique in its ability to induce lytic cell death in CHO-K1 cells. We determined that EV71:TLLcho successfully infects CHO-K1 cells owing to adaptive mutations in the capsid protein region. When we evaluated four non-synonymous mutations in VP1 and VP2 (out of the 23), which are predicted to be exposed on the virus surface, none of these mutations were sufficient to enable entry of EV71:BS into CHO-K1 cells. This was unexpected, considering our previous findings that three VP1 mutations (K₉₈ → E, E₁₄₅ → A, and L₁₆₉ → F) were necessary and sufficient to enable entry of EV71:BS into rodent cells (Victorio *et al.* 2016). Similarly, previous studies reported a single substitution in VP1-145 arising from mouse adaptation (Arita *et al.* 2008; Wang *et al.* 2011; Zaini and McMinn 2012) and monkey adaptation (Kataoka *et al.* 2015; Fujii *et al.* 2018). Our current findings do not fully support these previous observations and strongly suggest the need for cooperation of various adaptive mutations in the capsid to enable successful EV-A71 infection of a different host species. In the case of CHO cells or hamster infection, EV-A71 requires more than four capsid mutations for successful virus entry into hamster cells. Perhaps, it would be interesting to sequence the viruses re-isolated from EV-A71 infection models of hamster (Phyu *et al.* 2016) and gerbil (Xu *et al.* 2015) and compare with our findings.

Acknowledgements This research was fully funded by Temasek Lifesciences Laboratory Ltd. The pCMV-T7pol plasmid construct was a generous gift by Dr. Peter McMinn from Sydney University, Western Australia.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Animal and Human Rights Statement This article does not contain any studies with human or animal subjects performed by any of the authors.

References

- Arita M, Ami Y, Wakita T, Shimizu H (2008) Cooperative effect of the attenuation determinants derived from poliovirus sabin 1 strain is essential for attenuation of enterovirus 71 in the NOD/SCID mouse infection model. *J Virol* 82:1787–1797
- Dang M, Wang X, Wang Q, Wang Y, Lin J, Sun Y, Li X, Zhang L, Lou Z, Wang J, Rao Z (2014) Molecular mechanism of SCARB2-mediated attachment and uncoating of EV71. *Protein Cell* 5:692–703
- Fujii K, Sudaka Y, Takashino A, Kobayashi K, Kataoka C, Suzuki T, Iwata-Yoshikawa N, Kotani O, Ami Y, Shimizu H, Nagata N, Mizuta K, Matsuzaki Y, Koike S (2018) VP1 amino acid residue 145 of enterovirus 71 is a key residue for its receptor attachment

- and resistance to neutralizing antibody during cynomolgus monkey infection. *J Virol*. <https://doi.org/10.1128/JVI.00682-18>
- Kataoka C, Suzuki T, Kotani O, Iwata-Yoshikawa N, Nagata N, Ami Y, Wakita T, Nishimura Y, Shimizu H (2015) The role of VP1 amino acid residue 145 of enterovirus 71 in viral fitness and pathogenesis in a cynomolgus monkey model. *PLoS Pathog* 11:e1005033
- Liu CC, Chou AH, Lien SP, Lin HY, Liu SJ, Chang JY, Guo MS, Chow YH, Yang WS, Chang KH, Sia C, Chong P (2011) Identification and characterization of a cross-neutralization epitope of enterovirus 71. *Vaccine* 29:4362–4372
- Phyu WK, Ong KC, Wong KT (2016) A consistent orally-infected hamster model for enterovirus a71 encephalomyelitis demonstrates squamous lesions in the paws, skin and oral cavity reminiscent of hand-foot-and-mouth disease. *PLoS ONE* 11:e0147463
- Plevka P, Lim PY, Perera R, Cardoso J, Suksatu A, Kuhn RJ, Rossmann MG (2014) Neutralizing antibodies can initiate genome release from human enterovirus 71. *Proc Natl Acad Sci U S A* 111:2134–2139
- Reed L, Muench H (1938) A simple method of estimating fifty per cent endpoints. *Am J Hyg* 27:493–497
- Rossmann MG (1989) The canyon hypothesis. Hiding the host cell receptor attachment site on a viral surface from immune surveillance. *J Biol Chem* 264:14587–14590
- Victorio CB, Xu Y, Ng Q, Chow VT, Chua KB (2014) Phenotypic and genotypic characteristics of novel mouse cell line (NIH/3T3)-adapted human enterovirus 71 strains (EV71:TLLm and EV71:TLLmv). *PLoS ONE* 9:e92719
- Victorio CB, Xu Y, Ng Q, Meng T, Chow VT, Chua KB (2016) Cooperative effect of the VP1 amino acids 98E, 145A and 169F in the productive infection of mouse cell lines by enterovirus 71 (BS strain). *Emerg Microbes Infect* 5:e60
- Wang W, Duo J, Liu J, Ma C, Zhang L, Wei Q, Qin C (2011) A mouse muscle-adapted enterovirus 71 strain with increased virulence in mice. *Microbes Infect* 13:862–870
- Xu F, Yao PP, Xia Y, Qian L, Yang ZN, Xie RH, Sun YS, Lu HJ, Miao ZP, Li C, Li X, Liang WF, Huang XX, Xia SC, Chen ZP, Jiang JM, Zhang YJ, Mei LL, Liu SL, Gu H, Xu ZY, Fu XF, Zhu ZY, Zhu HP (2015) Enterovirus 71 infection causes severe pulmonary lesions in gerbils, *Meriones unguiculatus*, which can be prevented by passive immunization with specific antisera. *PLoS ONE* 10:e0119173
- Yamayoshi S, Yamashita Y, Li J, Hanagata N, Minowa T, Takemura T, Koike S (2009) Scavenger receptor B2 is a cellular receptor for enterovirus 71. *Nat Med* 15:798–801
- Zaini Z, McMinn P (2012) A single mutation in capsid protein VP1 (Q145E) of a genogroup C4 strain of human enterovirus 71 generates a mouse-virulent phenotype. *J Gen Virol* 93:1935–1940
- Zaini Z, Phuektes P, McMinn P (2012) A reverse genetic study of the adaptation of human enterovirus 71 to growth in Chinese hamster ovary cell cultures. *Virus Res* 165:151–156