Induction of Antihuman C–C Chemokine Receptor Type 5 Antibodies by a Bovine Herpesvirus Type-4 Based Vector

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Bovine herpesvirus 4 (BoHV-4) is a promising vector for the delivery and intracellular expression of recombinant antigens and can thus be considered as a new prototype vaccine formulation system. An interesting, and actively pursued, antigen in the context of human immunodeficiency virus (HIV) infection prophylaxis (and therapy) is the C–C chemokine receptor type 5 (CCR5) co-receptor, whose blockage by specific antibodies has been shown to inhibit both viral entry and cell-to-cell transmission of the virus. Building on our previous work on the BoHV-4 vector system, we have engineered and tested a replication-competent derivative of BoHV-4 (BoHV-4-CMV-hCCR5ΔTK) bearing a human CCR5 (hCCR5) expression cassette. We show here that CCR5 is indeed expressed at high levels in multiple types of BoHV-4-CMV-hCCR5ΔTK-infected cells. More importantly, two intravenous inoculations of CCR5-expressing BoHV-4 virions into rabbits led to the production of anti-CCR5 antibodies capable of reacting with the CCR5 receptor exposed on the surface of HEK293T cells through specific recognition of the amino-terminal region (aa 14–34) of the protein. Given the growing interest for anti-CCR5 immunization as an HIV control strategy and the many advantages of virus-based immunogen formulations (especially for poorly immunogenic or self-antigens), the results reported in this study provide preliminary validation of BoHV-4 as a safe viral vector suitable for CCR5 vaccination.

Keywords: bovine herpesvirus 4, gene delivery vector, human CCR5, recombinant virus, antihuman CCR5 antibodies

INTRODUCTION

Bovine herpesvirus 4 (BoHV-4) is dsDNA genome virus belonging to Herpesviridae family, Gammaherpesvirus subfamily and Rhadinovirus genus. The natural host for BoHV-4 is the bovine; however, BoHV-4 presence has been detected from many other animal species. One of BoHV-4 features is its ability to replicate in vitro both in primary cultures and cell lines from various animal
species (1–7), and, in vivo, to experimentally infect many non-
natural hosts such as mice (5, 8, 9), rats (10), rabbits (4), sheep
(2), swine (11), and goats (7).

Ex vivo infection of non-human primate tissue explants has
also been observed (paper in preparation). This feature suggests
the use of BoHV-4 as a potentially competent viral vector for in vivo human cell transduction as well. In contrast to other
gamma-herpesviruses, there are neither growth-transformation
signals nor any virus-related pathology within the natural or
experimental hosts of BoHV-4. Recombinant BoHV-4, derived
from the cloned BoHV-4 genome in the form of a bacterial
artificial chromosome (BAC), able to express immune-dominant
antigens from different pathogens was successfully used
for immunization purposes in the abovementioned non-natural
host species without any apparent detrimental effect, overt clini-
cal sign or pathology causally related to viral vector inoculation
(2, 4, 5, 7–11). Furthermore, evident oncolytic properties in
immune-competent orthotopic syngeneic mouse and rat glioma
models were correlated to the herpes simplex virus-1 thymidine
kinase (HSV-1-TK) gene included into BoHV-4-based vector
genome (6).

The C–C chemokine receptor type 5 (CCR5) is not only
involved in leukocyte trafficking during inflammatory processes
but also serves as a major entry site and co-receptor for human
immunodeficiency virus (HIV) internalization and thus con-
tributes to intercellular spreading of the virus (12). The multiple
and overlapping (partially redundant) interactions between
chemokines and their receptors make CCR5 largely dispensable
in various contexts. This is reflected by the generally good
health of subjects homozygous for a 32 bp deletion in the coding
sequence of CCR5 (CCR5Δ32) that renders the protein dysfunctional (12).
Because of its role as a virus co-receptor, CCR5 represents a very
attractive target for preventing/controlling HIV infection and
multiple anti-HIV strategies centered on this receptor are being
developed (13). These include small-molecule CCR5 antagonists
approved for clinical use such as Aplaviroc (GlaxoSmithKline),
Maraviroc (Pfizer), and Vicriviroc (Schering-Plough). A second
approach, inspired by the protective effects documented for
natural as well as virus exposure-induced anti-CCR5 antibod-
ies (13–16), relies on anti-CCR5 vaccination as an innovative
anti-HIV strategy capable of providing effective protection or,
at least, reduced viral replication and spreading of the infection.
Importantly, naturally occurring or immunization-induced anti-
CCR5 antibodies have been shown to be capable of multi-clade
human papillomavirus blockage, a result that is rarely achieved
with the use of conventional HIV-based immunogens (17–21).

Despite the promising aspects of therapeutic application of
anti-CCR5 antibodies in the clinics, substantial bottlenecks need
to be overcome for their development and not only for CCR5
but also for G-protein-coupled receptors (GPCRs) in general.
GPCRs antigens are difficult to prepare, their extracellular region
is very variable, and the number of exposed epitopes is limited
(22). GPCRs have been prepared and delivered by different sys-
tems (22); however, viral delivery has seldom been investigated.

Taking into account, the promising properties of the BoHV-4
system and following-up to the above studies showing that anti-
CCR5 antibodies exert a protective effect against HIV infection,
we decided to explore the suitability of BoHV-4 as a vector for
the construction of a novel CCR5 immunogen. In this article,
we document the capability of an engineered BoHV-4 vector to
deliver and express a human CCR5 (hCCR5) expression cassette
in rabbits.

MATERIALS AND METHODS

Cells

Bovine embryo kidney ([BS CL-94] BEK, from M. Ferrari, Istituto
Zooprofilattico Sperimentale, Brescia, Italy), Dubai Camel cells
(ATCC® CRL-2276™, Dubca), BEK-expressing cre recombinase
(BEK cre) (3), human embryo kidney 293T ([HEK293T] ATCC:
CRL-11268™, and alpaca skin stromal cells (23) were cultured in
Eagle’s minimal essential medium (EMEM, Lonza) containing
10% fetal bovine serum (FBS), 2 mM l-glutamine (SIGMA),
100 IU/mL of penicillin (SIGMA), and 100 μg/mL streptomycin
(SIGMA) and 2.5 μg/mL of Amphotericin B (SIGMA) and
incubated at 37°C, 5% CO₂. R5-SupT1-transduced cell line are
CCR5-expressing cell lines referred to as SupT1-R5 clone M10
(medium expression of CCR5). The clone was obtained by
engineered SupT1 cells and kindly provided by H. Garg (24). The
cells (5 × 10⁶) were propagated in complete medium and sup-
plemented with 3 μg/mL of Blasticidin (Calbiochem, Germany).

Construct Generation

The hCCR5 ORF, was excised from (the commercial plasmid)
pcDNA3-hCCR5 (kindly provided by DR. Toon Laermans,
University of Brussels) cutting with MluI, blunt ended and
SmaI restriction enzymes. The ~2,900 bp hCCR5 fragment was
then cloned into SmaI cut pINT2 shuttle vector (2) to generate
pTK-CMV-hCCR5-TK.

Transient Transfection

HEK293T cells were seeded into six well plates (3 × 10⁵ cells/well)
and incubated at 37°C with 5% CO₂. When cells were sub-
confluent, the culture medium was removed, and the cells were
transfected with pTK-CMV-hCCR5-TK using polyethylenimine
(PEI) transfection reagent (Polysciences, Inc.). Briefly, 3 μg of
DNA was mixed with 7.5 μg PEI (1 mg/mL) (ratio 1:2.5 DNA-
PEI) in 200 μL of Dulbecco’s modified essential medium (DMEM)
high glucose (Euroclone) without serum. After 15 min at room
temperature, 800 μL of medium without serum was added, and
the transfection solution was transferred to the cells (monolayer)
and left for 6 h at 37°C with 5% CO₂, in a humidified incubator.
The transfection mixture was then replaced with fresh medium
EMEM, with 10% FBS, 100 IU/mL of penicillin, 100 μg/mL of
streptomycin, and 2.5 μg/mL of Amphotericin B (SIGMA) and
incubated for 24 h at 37°C with 5% CO₂.

BAC Recombineering and Selection

The PvuI linearized pTK-CMV-hCCR5-TK was used for heat-
inducible homologous recombination in SW102 E. coli contain-
ing the BAC-BoHV-4-A-TK-KanaGalK-TK genome targeted to
the TK locus with KanaGalK selector cassette. Recombineering
was performed as previously described (25) with some modifications.
After recombineering, only those colonies that were kanamycin
negative, and chloramphenicol positive were kept and grown overnight in 5 mL of LB containing 12.5 mg/mL of chloramphenicol. Selected SW102 E. coli clones carrying pBAC-BoHV-4 recombinants were analyzed by HindIII restriction enzyme digestion. Original detailed protocols for recombineering can also be found at the recombineering website (https://redrecombineering.ncifcrf.gov/background-info/what-is-recombineering.html).

**Southern Blotting**

To further confirm our results, a Southern blotting with a probe spanning human CMV promoter sequence, was performed. DNA from 1% agarose gel was capillary transferred to a positively charged nylon membrane (ROCHE), and cross-linked by UV irradiation by standard procedures (3). The membrane was prehybridized in 50 mL of hybridization solution (7% SDS, 500 mM sodium phosphate, pH 7.2) for 1 h at 65°C in a rotating hybridization oven (TECHNA INSTRUMENTS).

CMV probe labeled with digoxigenin was generated by PCR with CMV-KpnI-sense (5′-cagcctagctattataagtaaatc-3′) and CMV-KpnI-antisense (5′-cagcctagctgcatgatgatgatc-3′) primers, as previously described (4). The PCR amplification reaction was carried out in a final volume of 50 µL, containing 10 mM Tris–hydrochloride pH 8.3, 5% dimethyl sulfoxide, 0.2 mM deoxynucleotide triphosphates, 2.5 mM MgSO4, 50 mM KCl, and 0.25 µM of each primer. One hundred nanograms of DNA were amplified over 35 cycles, each cycle consisting of 1 min of denaturation at 94°C, 1 min of primer annealing at 55°C, and 1 min of chain elongation with 1 U of Pfu DNA polymerase (Fermentas) in a final volume of 200 µL of PBS–FBS 2% as suggested by BD Pharmingen™.

**Cell Culture Electroporation and Recombinant Virus Reconstitution**

Bovine embryo kidney or BEK cre cells were maintained as a monolayer with complete DMEM growth medium with 10% FBS, 2 mM L-glutamine, 100 IU/mL penicillin, and 100 µg/mL streptomycin. When cells were sub-confluent (70–90%), they were split to a fresh culture flask (i.e., every 3–5 days) and were incubated at 37°C in a humidified atmosphere of 95% air, 5% CO2. The supernatants of infected cultures were harvested after 24, 48, and 72 h, and the amount of infectious virus was determined by limiting dilution on BEK cells. Viral titer differences between each time point are the averages of triplicate measurements ± SEs of the means (P > 0.05 for all time points as measured by Student’s t-test).

**Viral Growth Curves**

Bovine embryo kidney cells were infected with BoHV-4-A and BoHV-4-CMV-hCCR5ΔTK at a MOI of 0.1 TCID50/cell and incubated at 37°C for 4 h. Infected cells were washed with serum-free EMEM and then overlaid with EMEM containing 10% FBS, 2 mM L-glutamine, 100 IU/mL penicillin, 100 µg/mL streptomycin, and 2.5 µg/mL Amphotericin B. The supernatants of infected cultures were harvested after 24, 48, and 72 h, and the amount of infectious virus was determined by limiting dilution on BEK cells. Viral titer differences between each time point are the averages of triplicate measurements ± SEs of the means (P > 0.05 for all time points as measured by Student’s t-test).

**Flow Cytometry Assay**

To evaluate the presence of hCCR5 protein on the cell surface, a flow cytometry assay was performed on pTK-CMV-hCCR5-TK-transfected HEK293T cells. Cells expressing the protein of interest and mock-transfected cells, which served as negative control, were both assayed with a FITC mouse-antihuman CD195 monoclonal antibody capable of binding to CCR5 Membrane Protein (Clone 2D7/CCR5, Catalog No. 555992, BD Pharmingen™).

The cells plated in a T75 cm2 were transfected with 22.5 µg of pTK-CMV-hCCR5-TK DNA, 67.5 µg of PEI (ratio 1:3 DNA-PEI) in 1.5 mL of DMEM high glucose (Euroclone) without serum. After 15 min at room temperature, 6 mL of medium without serum were added, and the transfection solution was transferred to the cells (monolayer) and left for 6 h at 37°C with 5% CO2, in a humidified incubator. After 6 h, the transfection mixture was then replaced with fresh medium EMEM, with 10% FBS.

The following day, the transfected cells were firstly briefly washed with sterile phosphate-buffered saline (PBS) to remove any traces of serum and subsequently detached with a PBS-ethylenedinitrilotetraacetic (EDTA) solution (50 µL of EDTA acid 500 mM in a final volume of 50 mL). 2 × 106 resuspended cells, for every sample to test, were centrifuged at 1,200 rpm for 4 min at R.T.

The pelleted cells were incubated at R.T. for 20 min with FITC mouse-antihuman CD195 monoclonal antibody, 1:40 diluted in a final volume of 200 µL of PBS–FBS 2% as suggested by BD Pharmingen. Moreover, 1 MOI of BoHV-4-CMV-hCCR5ΔTK was used to infect BEK, DUBCA, and alpaca cells checking the in vitro protein expression on the surface of infected cells by flow cytometry as described before.

Cells surface binding was also performed on Sup-T1-CCR5-M10 cells as previously described (27). Briefly, cells were incubated with 1:10 diluted serum in PBS with 3% FBS from pre-immunized and post-immunized rabbits for 1 h at 4°C, then the cells were washed with PBS and incubated with PE-conjugated goat anti-rabbit antiserum (Sigma-Aldrich) for 30 min at 4°C. Surface expressed CCR5 molecules were detected with anti-CCR5 monoclonal antibody 2D7-PE as the positive control.
control (PE-CF594, mouse-antihuman CD195 monoclonal antibody Becton Dickinson, CA, USA), which has given a mean fluorescence of 40.03. Negative control of binding was done using 5 × 10^4 cells incubated with PE-conjugated goat anti-rabbit antiserum (Becton Dickinson) for 30 min at 4°C. Ten thousand gated events were acquired using a FACSCalibur flow cytometer (Becton Dickinson). Live cells initially gated by forward and side scatter were analyzed by mean fluorescence intensity (MFI). MFI of each sample was calculated by subtracting MFI of negative control. The results are given as mean of MFI of two independent experiments.

Animal Handling and Vaccination
Rabbits were cared for and used in accordance with Italian laws for animal experimentation. Rabbits were maintained at 24°C with a controlled light cycle (12 h of light, starting at 6:00 a.m.) and with food and water ad libitum. Blood samples were obtained, and viral injections were performed via the auricular vein at scheduled intervals. In agreement with the current legislation on animal experimentation, which suggests to minimize the number of animals employed, two adult rabbits, after collection of the preimmune serum, were inoculated intravenously with 1 mL of 10^6 TCID50 of BoHV-4-CMV-hCCR5ΔTK. A second inoculation with an identical dose of BoHV-4-CMV-hCCR5ΔTK was done 2 weeks apart from the first inoculation. Blood samples were collected at 2 weeks, just before the second inoculum, and 5 weeks post vaccination serum were tested. After 1 h at R.T. incubation, cells were washed in PBS three times, and the cells were resuspended in PBS plus 1:40 FITC-conjugated goat anti-rabbit IgG (F0382, SIGMA) secondary antibody. After 30 min of incubation in the dark at 4°C, the samples were washed three times, resuspended in PBS and visualized on a plastic chamber slide with the fluorescence microscope Axiosverter S100 (Zeiss). Images were achieved using a digital CCD camera, and images were processed using the AxioVision 40-V4.6.3.0 (Carl Zeiss, Imaging Solution) software program.

Synthesis of Peptides
Peptides were synthesized by the solid-phase Fmoc method (28) using an Applied Biosystems model 433A peptide synthesizer. After peptide assembly, resin-bound peptides were deprotected as previously described (29) and purified to greater than 95% purity by semipreparative reverse-phase high-performance liquid chromatography. To obtain conformationally restricted etherocyclic peptides, an extra cysteine was added at peptides sequence from aa 14 to 34 as it has been demonstrated to be immunogenic whereas peptide from 1 to 13 did not induce antibodies (20, 21); ECL1 as constrained peptide, as its linear form did not elicit antibodies (19–21); ECL2 and ECL3 regions in their linear sequence.

CCR5-Specific ELISA
To quantify the rabbit serum antibodies against CCR5, micro-well plates were coated with synthetic peptides covering the

| TABLE 1 | Binding of CCR5-specific rabbit antiseras (#1 and #2) to extracellular region peptides of CCR5 and to CCR5 expressed by the cell line Sup-T1-I. |
|---|---|---|---|
| Assays | Peptides covering CCR5 extramembrane regions | Sequence | Rabbit antiserum #1 | Rabbit antiserum #2 |
| ELISA* | N terminus (aa 14–34) | YYTESPCQKIKNKOIAARLLP | <20–540 | <20–180 |
| | ECL1 (aa 89–102) | YAAAQWDGFQMTCMQ | <20–<20 | <20–<20 |
| | ECL2 (aa 178–197) | CSSHPYSQOYPKKN FOTLK | <20–<20 | <20–<20 |
| | ECL3 (aa 260–274) | FOFGGLNNCSSSRN | <20–<20 | <20–<20 |
| | Biotinylated constrained ECL1 (aa 89–103)** | kgcYAAAQWDGFQMTCMQgk | 2.4–9.14 | 2.7–13.17 |

*ELISA results are expressed as titers (serum dilution 1/n).

**Constrained peptide has been obtained introducing an extra cystein.

Flow cytometry results are expressed as mean fluorescence intensity.

Immunofluorescence Antibody Test (IFAT) Assay
To evaluate the presence of anti-CCR5 antibody, an immunofluorimetric assay was performed on pTK-CMV-hCCR5-TK-transfected and mock-transfected HEK293T cells and treated with the serum of BoHV-4-CMV-hCCR5ΔTK-vaccinated rabbits. The cells plated in a T75 cm^2 were transfected with 22.5 µg of pTK-CMV-hCCR5-TK DNA, 67.5 µg of PEI (ratio 1:3 DNA-PEI) in 1.5 mL of DMEM high glucose (Euroclone) without serum. After 15 min at room temperature, 6 mL of medium without serum was added, and the transfection solution was transferred to the cells (monolayer) and left for 6 h at 37°C with 5% CO_2, in a humidified incubator. After 6 h, the transfection mixture was then replaced with fresh medium EMEM, with 10% PBS.

24 h after the transfection, the cells were firstly briefly washed with sterile PBS to remove any traces of serum and subsequently detached with sterile PBS. After three PBS washes, the cells were resuspended in PBS plus rabbit serum diluted to 1:20; preimmune and 5 weeks post vaccination serum were tested. After 1 h at R.T. incubation, cells were washed in PBS three times, and the cells were resuspended in PBS plus 1:40 FITC-conjugated goat anti-rabbit IgG (F0382, SIGMA) secondary antibody. After 30 min of incubation in the dark at 4°C, the samples were PBS washed three times, resuspended in PBS and visualized on a plastic chamber slide with the fluorescence microscope Axiosverter S100 (Zeiss). Images were achieved using a digital CCD camera, and images were processed using the AxioVision 40-V4.6.3.0 (Carl Zeiss, Imaging Solution) software program.
extra membrane regions of CCR5 (amino-terminal, ECL1, ECL2, and ECL3 as shown in Table 1), at 0.1 µg/well in 50 mM carbonate buffer, pH 9.5, for 1 h at 37°C. The plates were saturated for 1 h with 1% milk (Sigma-Aldrich, MO, USA) in PBS. Serial dilutions (from 1:20 up to 1:4,860 by threefold dilutions) of pre-immunized and post-immunized specific antisera were added to 1% milk and 0.1% Tween 20 (Sigma-Aldrich) in PBS. Then, peroxidase-conjugated goat anti-rabbit total IgG (Sigma-Aldrich) was added and incubated for 30 min at 37°C. The enzymatic reaction was developed with the TMB Microwell Peroxidase Substrate System (KPL, MD, USA) and read in a plate reader (Biotek, VT, USA) at 492 nm. The reciprocal endpoint titers were determined as the last sample dilution that produced a threefold greater absorbance than the ones of the sample diluent and expressed at serum dilution 1/n. Two independent experiments have been performed, and results are expressed as mean value of titers. To quantify antibodies directed to conformational epitope of ECL1, avidin (Sigma-Aldrich) was coated at 1.5 µg/well in 50 mM carbonate buffer, pH 9.5 and then biotynilated-ECL1 constrained peptide was used. The rest of the assay was similar as for the ELISA performed with the other CCR5 peptides but using 10% bovine serum albumin (Sigma-Aldrich), 30% fetal calf serum from Lonza, Belgium, and 0.1% Tween 20 in PBS as either blocking or diluent buffer (19).

RESULTS AND DISCUSSION

The first step of this study was to generate a recombinant BoHV-4 derivative capable of delivering a hCCR5 expression cassette. Starting from a pCMV-hCCR5 plasmid vector containing the hCCR5 ORF under the control of the CMV promoter and the bovine growth hormone polyadenylation signal (BGHpA), the entire expression cassette (CMV-hCCR5-BGHpA) was excised by restriction digestion and sub-cloned into the pINT2 shuttle vector. pINT2 contains two BoHV-4 TK flanking sequences (1) that were used to generate the targeting vector pTK-CMV-hCCR5-TK. In fact, the BoHV-4 TK genomic locus can harbor foreign DNA sequences of varying length (up to 20 kbp) without any impairment of in vitro viral replication nor expression of the corresponding heterologous proteins. hCCR5 expression was functionally proved by pTK-CMV-hCCR5-TK HEK transient transfection into 293 T cells and by immunoblotting and flow cytometry detection using an anti-hCCR5 monoclonal antibody. As shown in Figures 1A,B, hCCR5 was well expressed on the surface of transfected HEK293T cells.

![Figure 1](image-url) | Flow cytometric analysis of human CCR5 (hCCR5) on the cell surface of pTK-CMV-hCCR5-TK-transfected HEK293T cells. The blue line corresponds to mock-transfected cells, and the red line corresponds to the pTK-CMV-hCCR5-TK-transfected cells. (A) To analyze pTK-CMV-hCCR5-TK- and mock-transfected cells, a FITC-conjugated anti-isotype antibody, which served as negative control antibody, was assayed. (B) To analyze pTK-CMV-hCCR5-TK and mock-transfected cells, a FITC-conjugated anti-hCCR5 antibody was used. The consistent shift of the red lane indicates the cell surface staining of pTK-CMV-hCCR5-TK-transfected cells with respect to the mock-transfected control.
Restriction enzyme linearized pTK-CMV-hCCR5-TK was then recombined into pBAC-BoHV-4-A-KanaGalKΔTK contained in SW102 E. coli cells by heat-inducible homologous recombination, to generate pBAC-BoHV-4-CMV-hCCR5ΔTK (Figure 2A). HindIII digestion and Southern blotting were performed to analyze selected clones (Figure 2B). Because altered bacterial phenotypes due to aberrant recombinase transcription can be generated through heat-inducible recombination and repeated passages in bacteria, SW102 E. coli cells carrying pBAC-BoHV-4-CMV-hCCR5ΔTK were serially cultured for 20 passages and the corresponding BAC DNAs were repeatedly checked by HindIII digestion analysis. Throughout the various passages,
Figure 3

Flow cytometric analysis of bovine herpesvirus 4 (BoHV-4)-CMV-hCCR5ΔTK infected cells. Alpaca (A), bovine (B), and camel (C) cell lines expressing human CCR5 (hCCR5) on their surface were analyzed. The blue line corresponds to BoHV-4 infected, used as a negative control, whereas the red line corresponds to BoHV-4-CMV-hCCR5ΔTK infected cells. The consistent shift of the red lane indicates the cell surface staining of BoHV-4-CMV-hCCR5ΔTK-infected cells respect to the mock-transfected control. Efficiency of infection/transduction is indicated, 86, 99, and 95% for alpaca, bovine, and camel, respectively. Anti-isotype antibody control gave a complete overlapping of the two peaks for the three cell lines tested.

No restriction pattern differences were detected (Figure 2C), thus confirming clone stability.

To reconstitute infectious viral particles, pBAC-BoHV-4-CMV-hCCR5ΔTK was electroporated into BEK and BEKcre cells for the excision of BAC cassette. Both cellular lines allowed viable virus reconstitution (Figure 2D) and as attended the loss of the green fluorescence was observed in the viral progeny indicating the excision of the CMV-GFP expression cassette within the floxed BAC plasmid backbone. Since reconstitution of viable BoHV-4-CMV-hCCR5ΔTK required a longer time than reconstitution of the parental BoHV-4-ΔTK (3 and 4 days, respectively), it was of interest to know if hCCR5, encoded by the expression cassette integrated into the viral genome, might have a detrimental effect on viral replication. As shown in Figure 2E, no significant difference was observed between the growth (replication) performance of the recombinant BoHV-4-CMV-hCCR5ΔTK virus and the empty BoHV-4-ΔTK controls, thus indicating the replication competence of the BoHV-4-A BAC derivative containing the CMV-hCCR5-BGHpA expression cassette.

More importantly, cells from different artiodactyl infected with BoHV-4-CMV-hCCR5ΔTK and assayed by flow cytometry, robustly expressed membrane-associated hCCR5 (Figure 3).

Next, immunogenicity of BoHV-4-CMV-hCCR5ΔTK was tested in rabbits. In accordance with European laws, which emphasize minimizing the number of animals utilized for pre-clinical experimentation, BoHV-4-CMV-hCCR5ΔTK was inoculated into only two rabbits. 1 mL of 10⁵ TCID₅₀/mL of BoHV-4-CMV-hCCR5ΔTK was intravenously inoculated into adult rabbits, after preimmune serum collection. 2 weeks after the first immunization the inoculation was identically repeated. Collection of blood samples was performed 3 weeks after the last inoculation, at which time none of the animals developed fever or other adverse effects attributable to immunization (Figure 4A) and this was in agreement with previously published data (4). As demonstrated by an IFAT conducted on pTK-CMV-hCCR5-TK-transfected HEK293T cells (Figure 4B), both immunized animals mounted an anti-hCCR5 antibody response.

Furthermore, as revealed by hCCR5 peptide mapping in ELISA, the humoral immune response elicited by BoHV-4-CMV-hCCR5ΔTK was directed against the hCCR5 amino-terminal region comprised between amino acids (aa) 14–34, which represents the most immunogenic region in this experimental setting (Table 1).
Alterations of self-antigens can be induced by viral infection rising auto-immunogenic proteins and their corresponding autoantibodies. Conformational changes in host receptors and self-proteins reshaping of non-self-antigenic epitopes can occur in response to host factors or other latent or concomitant viral infections, causing perturbations in host cells (30).

Previous immunization experiments in mice have demonstrated the feasibility of breaking self-tolerance and inducing significant levels of anti-CCR5 antibodies with the use of appropriate, non-live recombinant antigens (20, 31). In this context, live virus-based antigen formulation systems deserve special attention because of their relative ease of production and ability to deliver the antigen expression cassette directly into host cells, thus allowing high-level expression of the antigen as well as a widespread distribution of transduced cells, ultimately leading to a superior immunogenicity via a cross-priming mechanism. It should be noted, however, that the immune system has evolved multiple mechanisms to detect and eliminate invading viruses and that different viral vector systems may be differently suited for diverse and specific immunization purposes. Considering this, the viral vector can be used as an adjuvant and a delivery system. To stimulate an optimized immune response, an efficient viral vector should remain in the host organism long enough to express the antigen.

**FIGURE 4** | Rabbit immunization. (A) Diagram showing rabbit immunization scheme and blood sample collection. (B) Representative microscopic immunofluorescence antibody test images (magnification, 10×) of HEK293T cells transfected with pTK-CMV-human CCR5 (hCCR5)-TK or mock transfected and challenged with sera from BoHV-4-CMV-hCCR5ΔTK-immunized rabbits. The presence of anti-hCCR5 antibodies in the rabbit serum samples (5 weeks post immunization) is detectable by green cells when observed with FITC filter. Negative controls were established with preimmune sera.
as an immune target. Preexistence of anti-vector immunity in the host organism is one of the major obstacles for the development of a vaccine vector. BoHV-4 is able to bypass this barrier because it does not naturally stimulate serum neutralizing antibodies production. Compared to DNA vaccines, virus vaccines are more stably storable and useful for multiple purposes. Moreover, DNA-based vaccines present lower relative efficacy, requiring high doses of multiple boosts (up to 500 µg of plasmid DNA per injection) in order to obtain similar responses to those of attenuated virus vaccination.

Given the unpredictable performance of different viruses as antigen carriers, experimental testing of individual viruses is required to identify the best suited vaccine vector agent. The data presented in this pilot-study, which clearly point to the potential of BoHV-4 as a gene delivery vector capable of conferring immunogenicity to poorly antigenic (and self) proteins such as hCCR5, represent a first step in this direction. This innovative approach, together with other immune-modulating strategies, could lead to new treatment perspectives both for HIV/AIDS and other disorders characterized by detrimental pro-inflammatory responses.

**AVAILABILITY OF DATA AND MATERIAL**

Available under request.

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**ETHICS STATEMENT**

Animal experiments were conducted in compliance with national (Decreto Legislativo numero 26, 4 Marzo 2014) and international laws and policies (Guide for the Care and Use of Laboratory Animals). The present project was approved by the Ethical Committee of the University of Parma (OPBA: prot. n. 49/13 del 08/07/2013).

**AUTHOR CONTRIBUTIONS**

GD conceived the experiments and wrote the paper. AV, VF, GT, FM, VM, CP, and GD performed the experiments. GD, LL, SC, and SO analyzed the data.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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