Detection, characterization, and enrollment of donors of Ebola convalescent plasma in Sierra Leone

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BACKGROUND: Passive therapy with convalescent plasma provides an early opportunity to intervene in Ebola virus disease (EVD). Methods for field screening and selection of potential donors and quantifying plasma antibody are needed.

STUDY DESIGN AND METHODS: Recombinant Ebola virus glycoprotein (EBOV GP) was formatted into immunoglobulin G-capture, competitive, and double-antigen bridging enzyme immunoassays (EIAs). EVD survivors in Freetown, Sierra Leone, were recruited as potential plasma donors and assessed locally using sera alone and/or paired sera and oral fluids (ORFs). Uninfected controls comprised unexposed Gambians and communities in Western Area, Sierra Leone. Antibody neutralization in selected sera was measured retrospectively in a pseudotype virus assay.

RESULTS: A total of 115 potential donors were considered for enrollment: 110 plasma samples were concordantly reactive in the three EIAs; three were concordantly unreactive and two were reactive in two of three EIAs (98.2% agreement; 95% confidence interval [CI], 93.9%-99.8%). In 88 donors with paired ORF and plasma, G-capture EIA reactivity correlated well in the two analytes ($R^2 = 0.795$). Plasma and ORF from 44 Gambians were unreactive. ORF samples from 338 of 339 unexposed Western Area community controls were unreactive (specificity, 99.7%; 95% CI, 98.4%-99.7%); ORF samples from 113 of 116 Kerry Town EVD survivors were reactive (sensitivity, 97.4%; 95% CI, 92.5%-99.5%). Strong reactivity in G-capture and/or competitive EIAs identified donors with high plasma EBOV GP antibody levels in the double-antigen bridging assay, correlating with high levels of neutralizing antibody.

CONCLUSIONS: In-field testing can qualify convalescent donors for providing high-titer antibody.

By late 2014 the outbreak of Ebola virus disease (EVD) was unchecked in Guinea, Liberia, and Sierra Leone. The potential efficacy of convalescent plasma (CP) as a treatment for EVD, first described in the 1995 Kikwit outbreak,1-3 led the World Health Organization (WHO) to consider development of CP therapy a priority.4,5 CP has been used for other viral infections3 and we have previously shown6 the importance of serologic confirmation of potential plasma donors rather than relying on a syndromic diagnosis alone.

ABBREVIATIONS: CP = convalescent plasma; DABA = double-antigen bridging assay; EBOV = Ebola virus; ETU = Ebola treatment unit; EVD = Ebola virus disease; GMT = geometric mean titer; GP = glycoprotein; IC50 = 50% reduction of virus infection; NOD = normalized optical density; ORF(s) = oral fluid(s); TM = transport medium.

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The antibody response after clinical EVD appears long-lived and correlates with the presence of neutralizing antibody. Nonhuman primate studies have shown that antibody to EBOV envelope glycoprotein (EBOV GP) protected against disease progression. A priori, and supported by these studies in nonhuman primates, we decided to ensure that human CP was drawn only from donors with plasma levels of EBOV GP antibody likely also to contain high levels of neutralizing antibody. To deliver this aspiration new serologic methods for the detection and qualification of immune donors were needed. The development of assays was undertaken, including for noninvasive samples, to provide initial screening as well as the identification of those seropositive potential donors with higher antibody levels. In spite of previous attempts to use nonblood analytes including oral fluid (ORF) for Ebola serology being unsuccessful, recognizing the widespread use of ORF in clinical virology, we also elected to pursue this approach. The enzyme immunoassays (EIAs) had to be specific and semiquantitative, preferably including noninvasive protocols, and sufficiently robust to be transported and used in the field in the absence of a cold chain. A series of EIA formats were constructed using the recombinant EBOV GP antigen employed by Qiu and colleagues. The use of these EIAs, including a noninvasive test using ORF, for facilitating the identification, recruitment, and qualification of convalescent blood donors as a potential source of therapeutic CP is described.

MATERIALS AND METHODS

Potential donors

The study “Convalescent plasma for early Ebola virus disease in Sierra Leone” (ISRCTN13990511 and PACTR201602001355272) was approved by the Sierra Leone Ethics and Scientific Review Committee, authorized by Pharmacy Board of Sierra Leone (PBSL/CTAN/MOHS-CST001) and sponsored by the University of Liverpool. The protocol is available on request (m.g.semple@liverpool.ac.uk).

Ebola virus disease survivors with certificates (issued by Ebola Treatment Centers on discharge) were recruited as potential donors through Military Hospital 34, Freetown, and the Sierra Leone Association of Ebola Survivors. Of 130 recruited and consented (Fig. 1), on average 6.1 months (range, 1-15 months; midquartiles, 4-8 months) after discharge, 12 were referred to the Ebola Survivors’ Clinic because of possible post EVD sequelae. A total of 118 well volunteers were referred to the blood bank in Freetown for final assessment. Three were excluded because of hepatitis B virus infection. The remaining 115 provided written consent to become qualified donors, giving 315 plasma samples and 205 ORF samples overall. In addition the first (#15/220) and the second (#15/252) WHO standards from the National Institute of Biological Standards and Controls were included as controls.

Unexposed controls, The Gambia

Forty-four individuals were enrolled by the Medical Research Council Unit, The Gambia, into a malaria field study and serum and ORF samples archived. Approval was given to test these locally for antibody to EBOV.

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Ebola_CP Consortium Investigators are listed in Appendix A.

The study “Convalescent plasma for early Ebola virus disease in Sierra Leone” (ISRCTN13990511 and PACTR201602001355272) was supported by the Wellcome Trust (Award 106491) and Bill and Melinda Gates Foundation; Public Health England Ebola Emergency Response; and the Blood Safety Programme, National Health Service Blood and Transplant. JTS was supported by the European Union Horizon 2020 research and innovation program (Grant 666094). The funders had no role in the collection and analysis of the samples, in the interpretation of data, in writing the report, nor in the decision to submit the paper for publication.

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Survivors and unexposed community controls, Sierra Leone

As part of a separate study on transmission within households\textsuperscript{14} ORF samples were taken from 116 polymerase chain reaction (PCR)-confirmed EBV survivors from Kerry Town Ebola Treatment Center, and 339 healthy volunteers living in three communities in Western Area Sierra Leone, which had no recorded cases of EVD. These samples were analyzed in Makeni, Sierra Leone. This study was approved by the Sierra Leone Ethics and Scientific Review Committee and by the ethics committee of the London School of Hygiene and Tropical Medicine. Written consent was sought from all participants or their parents or guardians if under 18 years.

**ORF sampling**

The Oracol (S10, Malvern Medical Developments Limited) ORF sampling kit was used. In Connaught blood bank the oral swabs were demonstrated by blood bank staff and then self-administered by donors. The swab was run along the upper and lower gum margins on either side of the mouth for 30 seconds each (2 min total) before returning it to the sampling tube. Samples were tested on receipt or stored at \(-20^\circ\text{C}\) within a day of collection.

For the Kerry Town survivors and the community controls the oral swabs were demonstrated by the field staff and then self-administered, with adults helping children. Each swab was rubbed firmly on the gums for 90 seconds, sealed, put in a cool box, transferred daily to the laboratory, and tested on receipt or stored at \(-20^\circ\text{C}\) as above.

**Sample handling**

Whole blood samples from potential donors were separated within 24 hours of venesection. All plasma samples...
received in Public Health England Colindale were tested for EBOV RNA. Fresh ORFs or frozen ORFs that had been thawed at room temperature were extracted by adding 1 mL of transport medium (TM) to the tube, agitating the swab in the TM within the tube, removing the swab with a circular motion, dispelling ORF and TM from the swab to provide the ORF extract, which remained in the tube. Plasma samples and ORF extracts were stored at 4°C for up to 24 hours to allow testing before long-term storage at –20°C.

EIAs

Three solid-phase microplate EIAs were formulated, based on the EBOV Mayinga GP antigen (rGP/TM, IBT Bioservices, Inc., USA Cat. 0501-016). In brief, the first was an immunoglobulin (Ig)G-specific reverse capture assay (G-capture EIA) using horseradish peroxidase (HRP)-labeled EBOV GP. The second was a simultaneous competitive assay (competitive EIA) using HRP-labeled monoclonal antibody (MoAb; 4G7) raised against EBOV GP. The third was a double-antigen bridging assay (DABA) using HRP-EBOV GP performed qualitatively or quantitatively to measure antibody to EBOV GP (full details of assays, critical reagents, and information for use leaflets in the Supplementary Information, available as supporting information in the online version of this paper). Both latter assays would be expected variously to detect IgM antibody, the competitive less so because of expected antibody low avidity in acute infection, the DABA more so because of the pentameric nature of IgM.

The positive control for the first two kits was plasma from a UK EVD survivor infected in Sierra Leone taken 1.5 months after discharge. The DABA EIA used a pool of five reactive donor plasmas attributed 1000 arbitrary units/mL (au/mL). The negative control plasma came from unexposed UK blood donors.

Normalized optical density measures

Optical densities (ODs) were “normalized” as the ratio between the test sample and the cut-off. For G-capture and DABA, where a reaction is defined by a test sample giving an OD of at least the kit cutoff, the normalized optical density (NOD) value is derived by test sample OD/cutoff OD.

For the competitive EIA, where a reaction is defined by a test sample giving an OD of not more than the kit cutoff, the NOD value is derived by cutoff OD/test sample OD. Samples giving NOD of at least 1.0 are reactive.

Neutralizing antibody

The ability of a sample to neutralize the propagation of a single-cycle infectious EBOV GP pseudo-type, as previously described,16 was used to investigate a selected panel of CP samples (details in Supplementary Information). In brief, the envelope-deficient human immunodeficiency virus (HIV)-1 backbone pSG3Δenv from the NIH AIDS reagents repository (https://www.aidsreagents.org/) was complemented with the Ebola GP expressed in (pcDNA3.1 from Thermofisher). The Ebola GP is derived from the KP096421 early strain to which the coding changes appearing later in the epidemic (A81V, I317V, T229A, and N551D) were introduced. All analyses were performed in triplicate and repeated. The neutralizing ability of a sample was expressed as that dilution of plasma that provided a 50% reduction of virus infection (IC50).

Sample size and statistical analysis

The size of the potential donor panel was determined by the need for plasma for a planned therapeutic intervention study. Within- and between-assay variability was assessed as the percentage of coefficient of variation (CV; i.e., standard deviation/mean) using paired testing of samples and from repeat testing of the positive kit control across runs. Results from different assays (DABA, G-capture, competitive) run on the same samples as well as G-capture run on paired plasma and ORF samples were compared by calculating R² values (square of the correlation coefficient) and as percentage agreement.

RESULTS

Test performance

For the G-capture EIA, replicate testing within plates of 222 analytes (plasma or ORF) from the potential donors,
gave a mean CV of 2.9%; replicate testing of ORF samples from survivors and community controls gave an average CV of 8.0% within plates (23 samples) and 17.9% between plates (104 samples). For the competitive EIA, replicate testing within plates of 127 plasma samples from potential donors gave a mean CV of 9.1%. For the quantitative DABA on repeat testing the mean CV was 13%, the calibration plots demonstrated a CV of approximately 8%.

Control populations

Forty-four ORF and serum samples were tested in duplicate at Medical Research Council, The Gambia. With a cutoff of kit mean negative plus 0.1, no sample was considered reactive. The 16 serum samples with highest OD reactions were retested in the competitive EIA; all were unreactive.

In Sierra Leone, using the same cutoff of mean negative plus 0.1 OD, ORF from 338 of 339 individuals with no known exposure to EBOV infection were unreactive, giving a specificity of 99.7% (95% confidence interval [CI], 98.4%-99.9%). The one reactive sample (NOD = 1.4) was unreactive on further duplicate retesting. All other samples had NOD of less than 0.7. Among the 116 PCR-confirmed survivors from Kerry Town Ebola Treatment Center, 113 ORF samples were reactive on a single test, giving a sensitivity of 97.4%, (95% CI, 92.5%-99.5%).

Potential donors

Field testing of paired plasma and ORF samples from 10 convalescent donors tested using the G-capture EIA at Connaught Blood Bank in May 2015 demonstrated a clear correlation between the reactivity of plasma and ORF (Fig. 2; $R^2 = 0.822$). Tested at Connaught at the same time, 36 of 37 convalescent donor plasma samples, were reactive in both G-capture and competitive EIAs, with correlated reactivity levels (Fig. 3A; $R^2 = 0.625$). Further initial and repeat retesting was carried out at Public Health England Colindale. All 115 plasma samples were retested for EBOV RNA on receipt in the UK; all were negative. Eighty-eight paired plasma and ORF samples showed good correlation.
in reactivity on the G-capture EIA ($R^2 = 0.795$ using linear regression; Fig. 3B). One ORF sample was unreactive (NOD, 0.78), giving a sensitivity of ORF compared to plasma of 87 of 88, 98.9% (95% CI, 93.8%-99.97%). Two ORF samples, although reactive, had lower reactivity in the ORF G-capture test than expected from the plasma results (Fig. 3B). They had a low level of IgG in the ORF as sampled (<3 mg/L). One of these donors (ORF NOD, 3.2; plasma NOD, 12.0) had provided an unpaired ORF 3 days earlier which gave a NOD of 10.0.

Pooled normal human plasma from UK blood donors.

<table>
<thead>
<tr>
<th>Sample identity</th>
<th>G-capture EIA</th>
<th>Competitive EIA</th>
<th>DABA EIA (au/mL)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donor 1</td>
<td>0.02</td>
<td>0.15</td>
<td>3.20</td>
<td>&lt;35†</td>
</tr>
<tr>
<td>Donor 2</td>
<td>0.02</td>
<td>0.11</td>
<td>2.58</td>
<td>&lt;35†</td>
</tr>
<tr>
<td>Donor 3</td>
<td>0.07</td>
<td>0.38</td>
<td>2.53</td>
<td>&lt;35†</td>
</tr>
<tr>
<td>Donor 4</td>
<td>0.17</td>
<td>0.99</td>
<td>1.00</td>
<td>112</td>
</tr>
<tr>
<td>Donor 5</td>
<td>0.39</td>
<td>2.24</td>
<td>1.57</td>
<td>64</td>
</tr>
<tr>
<td>Positive control</td>
<td>3.65</td>
<td>20.87</td>
<td>0.14</td>
<td>1000</td>
</tr>
<tr>
<td>Negative control</td>
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<td>0.41</td>
<td>2.63</td>
<td>&lt;35†</td>
</tr>
<tr>
<td>Cutoff</td>
<td>0.17</td>
<td>1.00</td>
<td>1.39</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

* Plasma samples from Donors 1-3 inclusive were unreactive in any of the three tests used. Plasma sample from Donor 4 was unreactive in the G-capture EIA and plasma sample from Donor 5 was unreactive in the competitive EIA, both plasmas from Donors 4 and 5 contained detectable antibody to EBOV GP in the DABA EIA.
† Lower limit of detection in the run.

The competitive EIA had a GMT of 838 au/mL, and the 20 in both upper quartiles had a GMT of 934 au/mL. The subset of 25 samples chosen for investigation of neutralizing antibody had DABA antibody levels ranging from 200 to more 4000 au/mL, reflecting the range of reactivity of donor samples in this assay. There was a close correlation between DABA reactivity and IC$_{50}$ titers of neutralizing antibody ($R^2 = 0.763$, Fig. 5B). A similar correlation between the level of neutralizing antibody and reactivity in the G-capture EIA was also seen for the paired plasmas ($R^2 = 0.679$, Fig. 5A) and ORFs from 21 of the same donor samplings where ORF data were available ($R^2 = 0.570$, Fig. 5C). The neutralization IC$_{50}$ of both the first (#79 NIBSC 15/220) and the second (#92 NIBSC 15/262) WHO standards are as shown at 162 and 192, respectively (Figs. 5A and 5B).

**DISCUSSION**

We have shown that recruitment and screening of potential CP donors to exclude seronegative individuals and to select those with higher antibody levels is possible in a resource-poor setting during an EVD outbreak. Furthermore, the high sensitivity and specificity of the tests developed and the comparable performance of the G-capture EIA when used on ORFs have implications beyond the identification of donors, as they enable large-scale noninvasive serologic studies.¹⁴

Seronegative individuals were, however, rare among potential donors (3/115). Although all potential donors
possessed certificates indicating discharge from an Ebola treatment unit (ETU), in the societal turmoil of an ongoing epidemic and resulting deprivation it is not surprising that certification may not be secure. Although recruitment was facilitated by certification and financial incentive, it is clearly appropriate to use serology to qualify donors for therapeutic purposes. The seronegative donor of Plasma Sample 1 (Table 1) was diagnosed before admission to the ETU with a high viral load, which became undetectable within 48 hours suggesting an erroneous first PCR procedure. On further inquiry, no record of EBOV PCR testing could be found nationally for the seronegative donors of Plasma Samples 2 and 3. If these three are truly seronegative as these data would infer, the G-capture EIA identified 111 of 112 (99.1%; 95% CI, 95.1%-99.98%).

Oral fluid testing provides acceptable noninvasive sampling, used widely in clinical virology and is valuable in acute outbreaks and seroepidemiologic studies. The ORF EIA also correlated with EBOV candidate vaccine response in UK volunteers. The negative G-capture results from a nonexposed population in The Gambia indicated good specificity. This was confirmed in the unexposed community controls from Sierra Leone (338/339 negative; specificity, 99.7%) while the sensitivity of the G-capture EIA on ORF remained high (113/116 Kerry Town EVD survivors positive; sensitivity, 97.4%). Furthermore, the clear association between reactivity of ORF and plasma (Figs. 2 and 3B) demonstrates that ORF is appropriate for investigating the spread of EBOV in diverse communities as well as selection of seropositive donors. Previous studies were unable to detect EBOV antibody in ORF samples reflecting the poor sensitivity of indirect EIAs for ORF studies. This is not the case for reverse G-capture EIAs. However, the ORF sample must be taken adequately to avoid false negatives from low-ORF IgG levels; it would not normally be possible in the field to check total IgG levels in the ORF.

A competitive EIA incorporating a MoAb to a well-defined neutralizing epitope confirmed the specificity of the ORF G-capture EIA, but requires a plasma sample. The use of EIAs of different format has long been considered advantageous in the terms of specificity and this same principle should apply to EBOV serology. Choice of the EBOV GP antigen for serology was driven by availability, by the previous selection of this GP for vaccine studies and the generation of protective murine MoAb. This, however, does not imply that antibody to EBOV GP is necessarily the only therapeutic component of CP.

Having an antigen-coated solid phase and a directly conjugated GP, it was a natural extension to develop a double-antigen bridging EIA for antibody quantification. Measurement of the level of reactivity in a capture or competitive assay has subtly different implications. A capture assay reaction depends on the proportion of the antibody present in the analyte that recognizes the antigen and the avidity with which the antibody interaction occurs. A competitive assay depends on the concentration of antibody present in the analyte and the avidity and specificity of that antibody. Usually a strong reaction in one EIA correlates with a strong reaction in the other EIA, but not necessarily with a direct linear relationship (Figs. 3A and 3C). When antibody to EBOV GP was quantified in the DABA EIA, levels differed widely between individuals and many survivors had very low levels of measurable antibody to GP. This suggests that alternative host determinants such as the cytotoxic T-lymphocyte response may be more important for survival and recovery than the...
humoral response. It also begs the question whether EVD survivors with low antibody levels are more susceptible to viral persistence or reactivation.

Both the G-capture and the competitive EIAs allowed selection of donors with high-level antibody (Fig. 4) quantified by DABA EIA, which in turn measures total antibody to EBOV GP. This selection, however, reduced the number of suitable donors available, so having a noninvasive initial screening method that could be used more widely was considered particularly useful. The range of antibody levels we observed across the cohort may explain the lack of clinical benefit found with the use of unselected CP in the trial in Guinea. Quantification of antibody to EBOV GP in DABA correlated with the measurement of biologically determined neutralizing antibody. Both assays also ranked the two WHO standards in the expected order of potency and the observed neutralization IC₅₀ titer were in agreement with published data. We believe that these observations indicate that the DABA EIA was suitable for quantifying biologically active antibody in the field. If the effect of CP depends on antibody dosing, it will be interesting to quantify neutralizing antibody in the full cohort of Sierra Leone donors.

The three different EIAs we have developed, their biologic plausibility, correlation with neutralizing antibody, and the excellent performance of the G-capture EIA on ORF providing a sensitive, specific, and noninvasive way of determining the EBOV serologic status of individuals, provide a suitable epitaph to our much loved and sadly missed colleague Dr Dhan Samuel.

APPENDIX A

Ebola_CP Consortium Investigators

The Ebola_CP: The Consortium Investigators for Ebola_CP (Convalescent Plasma for Early Ebola Virus Disease in Sierra Leone) are M.G. Semple (Consortium Lead Investigator) and J.T. Scott, (both Institute of Translational Medicine and NIHR Health Protection Research Unit in Emerging and Zoonotic Infections University of Liverpool, Liverpool, UK); S.M. Gevao (Country Lead Investigator), F. Sahr (Country Deputy Lead Investigator), C.P. Cole and J. Russell (all College of Medicine and Allied Health Sciences, Freetown, Sierra Leone); S. Baker, O. Kargbo, and P. Kamara (all National Safe Blood Service, Connaught Hospital, Ministry of Health & Sanitation, Freetown, Sierra Leone); M. Lado and C.S. Brown (King’s Sierra Leone Health Partnership, King’s Health Partners & King’s College London, London, UK); J. van Griensven, R. Ravinetto, and Y. Claeys (all Institute of Tropical Medicine, Antwerp, Belgium); R.S. Tedder, R. Gopal, and T.J.G. Brooks (National Infection Service, Public Health England, London, UK); C.C. Smith (Health Protection Scotland, UK); H.A. Doughty (NHS Blood and Transplant & College of Medical and Dental Sciences, University of Birmingham, Birmingham, UK); A. Mari Saez and M. Borchert (both Institute for Tropical Medicine and International Health, Charité, Berlin, Germany); A.H. Kelly (Department of Sociology, Philosophy and Anthropology, Exeter University, Exeter, UK); J.K. Baillie (The Roslin Institute, University of Edinburgh, Edinburgh, UK); N. Shindo, and D. Pfeifer (Department of
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RST and DS—concept and delivery of serologic development, field trial, data analysis, and manuscript drafting; SD, SN, and CSB—analytical processing and coordination of results and quality assessment; SI—data analysis, design, and delivery of figures and manuscript drafting; JTS—principal clinical lead in Sierra Leone and design and oversight of clinical standards; CC—shared clinical lead and governance in Sierra Leone; CCS—shared clinical lead and governance in Sierra Leone; TE—biostatistician for Ebola_CP; SB—clinical lead transfusion practice NSBS; OK and PK—principal transfusion scientists, field trial and serology in NSBS, and conduction of plasmapheresis; DN and UA—validation of EIAs in a low-risk population and manuscript drafting; GB—selection and provision of critical ancillary reagents for field kits and technical support; HAD—hemovigilance and support for plasmapheresis and manuscript drafting; CB—retrieval and collation of National Sierra Leone EBOV PCR data for CP donors; JvG—coordination with and support from parallel studies in Guinea and manuscript drafting; NA—statistical advice and analysis of numerical data; JRG—PI study of Kerry Town survivors and community controls and manuscript drafting; CA, GP, and WAP—oversight of neutralization testing and manuscript drafting; MGS—consortium lead investigator for Ebola_CP, conceiving the plasma intervention, design of serologic studies, and manuscript drafting.

CONFLICT OF INTEREST

The authors have disclosed no conflicts of interest.

REFERENCES


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