Monoclonal antibodies capable of reacting with a plurality of influenza virus A subtypes

The present invention in general falls within the field of immunology. More specifically, the invention concerns monoclonal antibodies directed against the HA (hemagglutinin) antigen of the influenza A virus.

BACKGROUND OF THE INVENTION

The annual influenza virus epidemics represent an important cause of morbidity and mortality throughout the world. In the United States of America it is estimated that more than 200,000 people are hospitalized each year for syndromes connected to influenza viruses, with about 40,000 deaths more or less directly related thereto (Thompson et al., JAMA, 2003, 289:179-186). Apart from these figures we must also consider the cases, in exponentially higher numbers, of infected subjects that stay at home for more or less long periods, with inevitable economic repercussions due to the loss of working days. A recent work (Molinari et al., Vaccine, 2007, 25: 5086-5096) has estimated the medical costs directly related to annual epidemics at 10.4 billions of US dollars per year, to which 16.3 billions of US dollars must be added for lost earnings due to absence from work. If in the calculation we consider other items too, such as the monetization of the economical losses linked to the death of the infected subjects, the amount rises to the incredible figure of 87.1 billions of US dollars. These economical data linked with the annual epidemics, together with a dreaded pandemic that could occur at any moment in the near future due to the appearance of influenza viruses new to man, explain the considerable interest in the search for effective strategies to contain the spread of these viruses.

Currently, the only available tool for facing the annual influenza epidemics in some way is an inactivated trivalent vaccine containing viral isolate antigens that presumably will be responsible for the epidemic of the next influenza season. This kind of prediction, based on epidemiological data linked to early isolations in some sentinel geographic areas, does not always turn out to be correct. Thus, there is a not at all negligible risk, which is present year after year, that the trivalent vaccine developed for a certain influenza season might prove

substantially ineffective.

In that case, as well as in the case of a new pandemic, the only available prophylactic/therapeutic aid would be to resort to the two available classes of antiviral drugs: the M2 protein inhibitors (amantadine and rimantadine), and the neuraminidase inhibitors (oseltamivir and zanamivir). However, in this situation too, a series of problems can be already expected, related both to the need to administer the antivirals in a very early stage of the infection, and to the rapid appearance, which has already occurred however, of resistant viral isolates.

An alternative effective strategy could be based on neutralizing antibody preparations directed against critical viral proteins and capable of recognizing portions of such proteins which are shared among the different isolates of influenza viruses.

For better understanding of the potential of an approach based on the passive administration of antibodies, it is useful to briefly mention the main structural features of the influenza viruses. The influenza viruses belong to the *Orthomyxoviridae* family and are characterized by the presence of an envelope derived from infected cell membranes, on which approximately 500 spikes are present, also referred to as projections. Such projections consist of trimers and tetramers from two important viral surface proteins: hemagglutinin (HA) and neuraminidase (NA). An integral membrane protein (M2) is also found on the envelope surface, which protein is present in much lower numbers compared to hemagglutinin and neuraminidase, and also organized in tetramers.

The influenza virus is further characterized by the presence, within the core, of a segmented genome comprised of 8 single stranded RNA fragments. Based on the features of some proteins within the virion (NP and M1), three influenza virus types are recognizable: type A, type B, and type C.

Type A and type B viruses are responsible for the annual epidemics. Instead, type C viruses are responsible for less severe syndromes.

Within type A viruses (the only ones responsible for pandemics and capable of causing the most severe syndromes even during annual epidemics), different subtypes are also recognizable based on the antigenic features of hemagglutinin and neuraminidase. The subtypes that have affected humans in the course of recent history are subtypes H1N1 and H3N2 (still circulating at present and contained in vaccine preparations), as well as subtype H2N2, no longer circulating since 1968 and responsible for the so called "Asiatic" flu in 1957. Other subtypes have sporadically affected humans (H9N2, H7N7, and the so dreaded recent H5N1 subtype), but they have not succeeded in spreading effectively and displacing the circulating subtypes.

The role of the surface proteins is essential in the viral replication cycle. In particular, hemagglutinin is the protein that allows the virus to recognize the sialic acid present on the surface of some cells, and to infect them. Instead, neuraminidase operates at the end of the viral replication cycle, that is during the release of new virus particles from the infected cells. Its function is to assist the release of hemagglutinin of the newly formed virions from the sialic acid present on the surface of the cell that produced them. The key role played by these two proteins, as well as their display on the virus surface, explain why they represent the main target of the immune response, and why they are susceptible to a high rate of mutation. In fact, the annual epidemics are caused by viruses that are more or less different from the ones of the previous years, and therefore are more or less effectively able to escape the immune response they stimulated. In other words, the progressive accumulation of point mutations in hemagglutinin (mostly) and neuraminidase (secondarily) makes the protective antibodies, produced in the course of previous epidemics, on the whole progressively ineffective.

The main protective role within the anti-influenza immune response is played by the humoral component. Antibodies exert their protective role primarily interfering with the binding of hemagglutinin to sialic acid, thereby preventing infection of the cells. Such a selective pressure determines the high rate of mutation in hemagglutinin. Sequence studies performed on H3 hemagglutinin subtype from 1968 through 1999 have revealed a total of 101

amino acid mutations (on a total of approximately 560 amino acids), with an average of about 3.5 mutations per year. 60% of mutations which occurred in the studied period were retained in the circulating viruses the following year too, indicative of the persistence of an immune-mediated selective pressure. 95% of these mutations were found in the HA1 hemagglutinin subunit, that is the one directly involved in the binding to sialic acid. Within such a high variability, however, some unchanged amino acid residues have been found, indicative of their essential role in the function of the protein. These hemagglutinin portions represent a potential target for a cross-neutralizing response towards the different subtypes of influenza viruses. However, it is predictable that such regions will not be able to induce an effective antibody response in most patients, since the fact that such targets hide in immunosilent areas has certainly represented a very favorable evolutionary step for the virus.

In fact, when referring to anti-influenza immunity, three different types of immunity must be taken into consideration, which can be well understood in the light of the data reported above:

HOMOLOGOUS IMMUNITY: related to the individual isolate. This type of immunity is always seen after an infection or a vaccination, but it provides a very limited protection against other isolates.

HOMOSUBTYPE IMMUNITY: related to isolates belonging to the same subtype. This type of immunity is often seen after an infection or a vaccination, but is lost when the mutation rate in hemagglutinin and/or neuraminidase increases considerably.

HETEROSUBTYPE IMMUNITY: related to isolates belonging to different subtypes. This type of immunity is extremely rare both in case of natural infection and in case of vaccination. From the strategic point of view, it is the most important immunity, as its presence and stimulation would be equivalent to the resistance to infection by every type A influenza virus.

Until a few years ago, it was thought that the heterosubtype immunity could be achieved just by stimulating effectively cellular immunity components directed against less mutated viral proteins, such as for example the NP protein that constitutes its core. However, recent

studies have shown that mice depleted of CD8 lymphocytes are still able to display a heterosubtype immunity, in contrast with mice depleted of the type B lymphocyte component (Nguyen HH, J Inf. Dis. 2001, 183: 368-376). An even more recent study has confirmed this data, highlighting a crucial role of antibodies, even if not neutralizing, directed precisely against epitopes that are conserved among the different subtypes (Rangel-Moreno et al. The J of Immunol, 2008, 180: 454-463).

OBJECT OF THE INVENTION

On the basis of the data reported above, one object of the present invention is to provide a monoclonal antibody, preferably human or humanized, reactive against the different subtypes of the influenza A virus.

Another object of the present invention is to provide a monoclonal antibody, preferably human or humanized, with neutralizing activity towards multiple subtypes of the influenza A virus.

Such an antibody would be an effective means of prevention when administered to patients at risk. Furthermore, the use of a human or humanized monoclonal antibody for human patients would give a further advantage, as the antibody would certainly be well tolerated.

Secondly, by constituting a component of the human antibody response to this virus, the monoclonal antibody with the above-mentioned features could represent a key factor for the design of innovative vaccines capable of inducing an extremely more effective, protective and broad-range immunity, compared to that induced by the currently used vaccines.

However, the achievement of monoclonal antibodies with such properties has so far proved to be extremely difficult.

The International patent application WO2007/134327, issued on November 22, 2007, describes Fab fragments capable, in ELISA assays, of binding to the HA antigen from various

isolates of the influenza A virus, subtype H5. However, this patent application does not provide an enabling description of antibodies capable of recognizing isolates belonging to different subtypes of the influenza A virus, nor does it describe in an enabling way the attainment of antibodies with actual neutralizing abilities towards influenza A viruses belonging to different subtypes.

Therefore, in spite of the fact that a monoclonal antibody with the ability to recognize and neutralize the different subtypes of the influenza A virus has been sought for a long time, such a need has so far remained frustrated.

DESCRIPTION OF THE INVENTION

The present inventors have surprisingly succeeded in providing monoclonal antibodies with the above-mentioned desirable features.

Thus, a first object of the present invention is a monoclonal antibody directed against the hemagglutinin antigen of the influenza A virus, characterized by being able to bind multiple subtypes of the influenza A virus.

A second object of the present invention is a monoclonal antibody directed against the influenza A virus, characterized by having a neutralizing activity towards multiple subtypes of the influenza A virus. Preferably, such a neutralizing monoclonal antibody recognizes influenza A virus hemagglutinin (HA) as the antigen.

The monoclonal antibodies of the invention are preferably human or humanized antibodies.

The attainment of human monoclonal antibodies according to the invention and their binding properties are described in detail in the experimental section that follows.

The preparation of humanized antibodies is performed by any per se known methodology, as for example described in Baca et al, 1997 J. Biol. Chem 272:10678-84 or Carter et al,

1992, Proc.Natl. Acad. Sci 89:4285. Such bibliographic references are provided exclusively for illustration and not limitation. In fact, other methodologies for the preparation of humanized antibodies are known in the prior art and can be used within the present invention.

The attainment of 6 clones (designated as INF4, INF16, INF28, INF39, INF43 and INF47) capable of producing monoclonal antibodies in the form of Fab fragments with the *in vitro* ability of binding multiple influenza A virus subtypes is specifically described in the following experimental section.

The monoclonal antibody produced by clone INF28 (designated as Fab28) represents one preferred embodiment of the invention, as the inventors have experimentally proved that this antibody displays a neutralizing activity towards multiple influenza A virus subtypes. For the sake of brevity, such an immunological property will sometimes be referred to herein below as "heterosubtype cross-neutralizing activity".

The Fab28 antibody is characterized by a heavy chain variable domain with the amino acid sequence SEQ ID NO:1 and a light chain variable domain with the amino acid sequence SEQ ID NO:2. The nucleotide sequence encoding for the heavy chain variable domain is SEQ ID NO:3 and the nucleotide sequence encoding for the light chain variable domain is SEQ ID NO:4.

In particular, the experimental section describes the manufacture of the monoclonal antibodies of the invention as Fab fragments. However, other antibody forms too, and the manufacture and use thereof are intended to be part of the scope of the invention. Non-limiting examples are whole immunoglobulins, or other kinds of antibody fragments, such as for instance $F(ab')_2$ fragments or antibody fragments smaller than Fabs, or peptides that have the same immunological properties as those experimentally demonstrated for the Fab of the invention.

Single chain antibodies can be constructed according to the method described in US patent

4,946,778 by Ladner et al., hereby included as reference. Single chain antibodies comprise the light and heavy chain variable regions linked by a flexible linker. The antibody fragment designated as single domain antibody is even smaller than the single chain antibody, as it comprises only one isolated VH domain. Techniques for obtaining single domain antibodies having, at least partially, the same binding ability as the whole antibody, are described in the prior art. Ward, et al., in "Binding Activities of a Repertoire of Single Immunoglobulin Variable Domains Secreted from *Escheria coli*," Nature 341:644-646, describes a screening method for obtaining the variable region of an antibody's heavy chain (VH single domain antibody) with a sufficient affinity for the target epitope to bind to it in an isolated form.

In the description that follows, the term "antibody" will then be used to refer to all the embodiments mentioned above, including whole immunoglobulins, Fab fragments or other antibody fragment types, single chain antibodies, single domain antibodies, etc.

The monoclonal antibodies of the invention may be generated and used in a free form or in a carrier-conjugated form. A carrier is any molecule or chemical or biological entity capable of conjugating with an antibody and making it immunogenic or increasing its immunogenicity. Non-limiting examples of carriers are proteins such as KLH (keyhole limpet hemocyanin), edestin, thyroglobulin, albumins as bovine serum albumin (BSA) or human serum albumin (HSA), erythrocytes such as sheep erythrocytes (SRBC), tetanus anatoxin, cholera anatoxin, polyamino acids such as for example poly(D-lysine:D-glutamic acid) and the like. In order to facilitate the binding of the antibody to the carrier, the antibody C-terminus or N-terminus may be modified, for example, by the insertion of additional amino acid residues, for instance one or more cysteine residues that are able to form disulfide bridges.

Because of their properties, which will be shown in detail in the experimental section that follows, the monoclonal antibodies of the invention (especially the antibody Fab28) are particularly suited for use in medical applications, particularly in the manufacture of a medicament for the broad-range prophylactic or therapeutic treatment of influenza A virus in-

fections.

Thus, the use of a monoclonal antibody of the invention, preferably the antibody Fab28, for the manufacture of a medicament for the prophylactic or therapeutic treatment of pathologies caused by influenza A virus infections, such as for instance the influenza syndrome, is within the scope of the invention.

In this context too, the expression "Fab28 antibody" includes not only the Fab fragments but also any other form into which the antibody can be prepared, for example whole immunoglobulins, other kinds of antibody fragments, single chain antibodies, etc.

As described in detail in the experimental section, the monoclonal antibodies have been obtained by molecular biology techniques starting from an EBV-transformed lymphocyte capable of producing cross-reactive monoclonal antibodies, thus able to recognize MDCK cell lysates infected with the two reference isolates as referred to herein below, which belong to different subtypes of the influenza A virus: H1N1, strain A/PR/8/34 and H3N2, strain A/PC/1/73. The specific procedures used to generate the transformed B cell lines from patients' peripheral blood are described in the experimental section.

In addition, the procedures used to clone the genes encoding the heavy and light chain variable portions of the Fab28 antibody of the invention are described in the experimental section, as well as the procedures to produce them recombinantly, both as single peptides and Fab fragments.

The ability of the monoclonal antibodies of the invention to react with cell lysates infected with different influenza A virus subtypes were verified by ELISA and immunofluorescence. In addition, a neutralizing assay was carried out in order to verify the *in vitro* biological activity of the antibodies. In this assay, the Fab28 antibody showed a heterosubtype cross-neutralizing activity towards the reference type A viral isolates as indicated above.

The obtained data suggest that the antibodies of the invention, especially antibody Fab28,

are extremely effective in conferring a passive immunity towards the influenza A virus to the subjects to whom they are administered, and that, accordingly, they are particularly useful in the broad-range prophylactic or therapeutic treatment of influenza A virus infections or pathologies directly or indirectly caused by influenza A virus infection. One example of such pathologies is the influenza syndrome.

In addition, the identification of the hemagglutinin conformational epitope that Fab28 binds to is described in the experimental section. Such a conformational epitope lies between hemagglutinin HA1 region and HA2 region and includes W357 and T358 residues on HA2 region and N336, I337 and P338 residues on HA1 region. The numbering of the residues is based on the hemagglutinin sequence from H1N1/A/PR/8/34 isolate in the database BLAST (SEQ ID NO: 5).

Thus, a further object of the invention is a pharmaceutical composition comprising an effective amount of a monoclonal antibody of the invention as the active ingredient and a pharmaceutically acceptable carrier and/or diluent. An effective amount is that which is able to induce a favourable effect in the subject to which the composition is administered, for example to neutralize the influenza A virus or interfere with the virus replication.

In this context, the term "subject" designates any animal host to which the composition can be administered, including humans.

Non-limiting examples of useful pharmaceutically acceptable carriers or diluents for the pharmaceutical composition of the invention include stabilizers such as SPGA, carbohydrates (for example, sorbitol, mannitol, starch, sucrose, glucose, dextran), proteins such as albumin or casein, protein-containing agents such as bovine serum or skimmed milk, and buffers (for example phosphate buffer).

The monoclonal antibodies of the invention can also be advantageously used as diagnostic reagents in an *in vitro* method for the detection of anti-influenza A virus antibodies with identical or similar neutralizing properties in a biological sample previously obtained from

a patient (such as for example a serum, plasma, blood sample or any other suitable biological material).

"Anti-influenza A virus antibodies with identical or similar neutralizing properties" are antibodies that display a heterosubtype cross-neutralizing activity versus the influenza A virus. These antibodies may be found in the biological sample from the patient as a result of a previous exposure to an influenza A virus, or because the patient had been previously administered a monoclonal antibody of the invention for therapeutic or prophylactic or research purposes.

An assay method for detecting, in a patient's biological sample, the presence of anti-influenza A virus antibodies having a heterosubtype cross-neutralizing activity, comprising contacting the said biological sample with a monoclonal antibody of the invention, as a specific assay reagent, is thus included in the scope of the invention.

The assay can be a qualitative or quantitative one. The detection or quantification of anti-influenza A virus antibodies having a heterosubtype cross-neutralizing activity may be carried out by, for example, a competitive ELISA assay. Thus, a diagnostic kit comprising a monoclonal antibody according to the invention as a specific reagent is also within the scope of the invention, the said kit being particularly designed for the detection or quantification of anti-influenza A virus antibodies having a heterosubtype cross-neutralizing activity towards the influenza A virus in a biological sample derived from a patient.

Similarly, the monoclonal antibodies of the invention (especially antibody Fab28) can be used as specific reagents in an assay method for detecting or quantifying, in a previously prepared immunogenic or vaccine composition, epitopes capable of evoking, in the subject to which such a composition has been administered, anti-influenza A virus antibodies having neutralizing properties identical or similar to those of the monoclonal antibody of the invention, that is a heterosubtype cross-neutralizing activity towards the influenza A virus.

Such a method is predicted to be useful for the assessment of any preparation to be used as

a vaccine or immunogenic preparation, as the recognition by the monoclonal antibody of the invention could be indicative of the presence, in the immunogenic preparation and/or vaccine, of one or more epitopes capable of stimulating the production of antibody clones capable of recognizing an advantageous epitope, such as for example an epitope capable of eliciting a heterosubtype immunity against the influenza A virus.

Finally, the monoclonal antibodies of the invention may be used for the manufacture of anti-idiotype antibodies according to methods per se known. Anti-idiotype antibodies are antibodies specifically directed towards the idiotype of the broad-range neutralizing antibodies used to prepare them, and as such are able to mimic the key epitopes they recognize.

Therefore, anti-idiotype antibodies directed against a monoclonal antibody of the invention are also included in the scope of the invention.

The following experimental section is provided solely by way of illustration and not limitation and does not intend to restrict the scope of the invention as defined in the appended claims. The claims are an integral part of the description.

EXPERIMENTAL SECTION

1. Selection of the patients

The patients enrolled in the study were selected so as to increase the chances of cloning cross-reactive anti-influenza antibodies, that is antibodies capable of recognizing, and potentially of neutralizing, influenza virus isolates belonging to different subtypes. In particular, it is described that some individuals, despite continuous exposure to the influenza virus (sometimes for professional reasons, as physicians, pediatricians, people working in kindergartens and schools), do not contract the disease. These rare individuals were thought to be less susceptible to influenza virus infection due to the development, for still unknown reasons, of an effective heterosubtype immunity. For this reason they were thought to be the best candidates for the generation of human monoclonal antibodies. In particular, the

following inclusion criteria were obeyed:

- between 25 and 55 years of age;

- recent pathological medical history, for the ten years preceding the study, negative for clinical influenza syndromes;

- antibody titer higher than 1:1000 against virus isolates, subtypes H1N1 and H3N2 responsible for the annual epidemics during the five years preceding the study;

- high neutralizing titer (IC50 >=1:400) against virus isolates, subtypes H1N1 and H3N2 responsible for the annual epidemics during the five years preceding the study;

- detectable neutralizing titer (IC50 >=1:20) against two reference subtype A virus isolates (A/PR/8/34 subtype H1N1; A/PC/1/73 subtype H3N2);

- no prior anti-influenza vaccination;

- compliance to receive anti-influenza vaccination.

At vaccination, and about 3 weeks post-vaccination, approximately 20 ml of blood were drawn from each patient into heparinized test-tubes.

2. Culture of the reference virus isolates

MDCK (Madin-Darby canine kidney) cells (ATCC® no. CCL-34TM) propagated in Modified Eagle Medium (MEM) (GIBCO), supplemented with 10% inactivated fetal bovine serum (FBS) (treatment at 56°C for 30 minutes) (EuroClone), 50 μg/ml penicillin, 100 μg/ml streptomycin (GIBCO) and 2 mM L-glutamine (EuroClone) were used as the cell line. The cells were incubated at 37°C in a 5% CO_2 atmosphere and were passaged at a 1:3 ratio twice a week. For the experiments described in this patent application, the following influenza virus isolates were used: H1N1, strain A/PR/8/34 (ATCC® no. VR-1469TM); H3N2, strain A/PC/1/73 (ATCC® no. VR-810), and strain B/Lee/40 (ATCC® no. VR-101). As the culture medium to grow the virus, MEM supplemented with 1 μg/ml serum-free trypsin (SIGMA) was used. The virus stocks were obtained from the culture supernatant as extracellular viruses. In short, after infecting the cells, the monolayer was observed daily to monitor the appearance of a cytopathic effect. Generally 4 days after the infection the supernatant was collected, centrifuged at 1000 RCF (relative centrifugal force) for 10 minutes

to eliminate the cell debris and filtered with 0.22 μm filters (MILLIPORE). The supernatant was then aliquoted and stored at -80°C as cell-free viruses.

3. Selection of monoclonal anti-influenza virus antibodies from peripheral blood B lymphocytes

The production of monoclonal antibodies from patients was carried out by using a transformation method via infection of B lymphocytes with Epstein-Barr virus (EBV), previously described by Cole et al, 1984 Cancer Research 22:2750-2753. The supernatant from the different clones obtained was assessed for the presence of antibodies by ELISA. Clones capable of producing IgG antibodies in the supernatant that are able to react in the ELISA against the cell lysates infected with the two reference isolates, subtypes H1N1 and H3N2, were then selected for a subsequent characterization. In particular, MDCK cells were infected with the aforesaid isolates at a high multiplicity of infection. About 48 hours post-infection, the cells were detached from the flask and washed twice in PBS. The cell pellets were then suspended in 300 μl of lysis solution (100mM NaCl, 100mM Tris pH 8 and 0.5% Triton-X) and stored in ice for 20 minutes. The cell debris were centrifuged away at 10000g for 5 minutes and the supernatant was stored at -20°C as a protein extract. As for the preparation of the control antigen, non-infected cells were treated in the same way. The supernatant protein concentration was determined in duplicate using the BCA™ Protein Assay Kit (Pierce). Briefly, the sample protein dosage was determined by referring to a standard curve obtained by a series of known-concentration dilutions of bovine serum albumin (BSA). The absorbance of every sample was measured with a spectrophotometer at a wavelength of 540nm. The lysates so obtained were then used (300 ng per well) to coat an ELISA plate (COSTAR) that was incubated at 4°C overnight. The following day, the plate was washed with distilled water and blocked with PBS/1% BSA (Sigma) for 45 minutes at 37°C. Then, 40 μl of supernatant from each clone were added to each well, which were incubated for 1 hour at 37°C. After 5 washings (WASHER ETI-SYSTEM, DiaSorin) with PBS/0.5% Tween-20 (Sigma), 40 μl of peroxidase-conjugated anti-human Fc (1:4000 in PBS/1% BSA, Sigma) were added to each well and the plate was incubated for 1 hour at 37°C. After 5 more washings with PBS/0.5% Tween-20, 40 μl of TMB peroxidase sub-

strate (Pierce) were added to each well. Approximately 15 minutes later, the enzymatic activity was blocked by adding 40 µl of H_2SO_4 and the signal was measured with a spectrophotometer set at 450nm. Special attention was given to the supernatant of six putative clones capable of producing cross-reactive antibodies (designated as cINF4, cINF16, cINF28, cINF39, cINF43 and cINF47, respectively), i.e. capable of recognizing both cell lysates infected with the strain belonging to subtype H1N1 and those infected with the strain belonging to subtype H3N2.

4. Preparation of Fab fragments from the cross-reactive clones

The genes encoding for the monovalent Fab chains capable of reacting with the influenza virus were cloned into a prokaryotic expression vector. This allows to avoid problems due to instability of antibody-producing cell clones, to better characterize the encoding genes from the molecular point of view, in order to have molecules that are certainly monoclonal at one's disposal, as well as increased amounts of each individual antibody.

The messanger RNA (mRNA) was extracted from the cultured clones and reverse transcribed using an oligo-dT according to methods per se known. The cDNAs encoding the light chain and the Fd fragment (i.e. the heavy chain portion present within the Fab fragment) were then amplified by described methods (CSH press, Phage display manual, ed. D.R.Burton, p. A1.6). The so obtained cDNAs were then cloned into an expression vector per se known, designated as pCb3/CAF (Burioni et al, J. Imm. Meth, 1988). In short, the gene (amplified DNA) encoding the heavy chain Fd portion of each Fab was digested with restriction enzymes XhoI and SpeI (Roche) for 1.5 hours at 37°C, and subsequently inserted into the vector's cloning site for heavy chains, in turn digested with the same enzymes. Instead, the light chains (amplified DNA) were digested with enzymes SacI and XbaI (Roche) and cloned into the vector similarly digested.

The so obtained recombinant constructs for each clone were used to electro-transform *E. coli* strain XL1Blue (made competent by cold washings in glycerol), according to standardized protocols for the use of 0.2 cm cuvettes (Voltage: 2500 V; Capacitance: 25 µF; Resis-

tance: 200 Ω). In parallel, the DNA sequences of the light chain variable part and the heavy chain variable part of the selected clones were analyzed. The sequences are those provided in the Sequence Listing. The molecular analysis of the mutational pattern showed a picture ascribable to antigen-induced somatic mutation processes for each of the clones.

5. ELISA assessment of the monoclonal Fabs obtained by cloning into PCb3/CAF

At completion of cloning, 40 recombinant bacterial clones for each monoclonal antibody were analyzed by ELISA using crude lysates from bacterial cultures obtained by heat shock. In particular, clones of bacteria transformed with the construct PCb3/CAF were inoculated into 10 ml of SB medium containing ampicillin and tetracycline at 50μg/ml and 10μg/ml, respectively, and were grown under shaking at 37°C until reaching an O.D.600 = 1. Subsequently, a specific inducer (IPTG - isopropylβ-D-thiogalactopyranoside) was added at the final concentration of 1mM and the culture was left shaking at 30°C overnight. The cells were lysed by heat shock (3 freeze/thawing rounds, at -80°C and 37°C, respectively) and then centrifuged to separate the cell debris from the Fab-containing supernatant. The soluble Fabs obtained were assayed by ELISA. 96-Well microtiter plates (Nunc) were coated with lysates from cells infected with the above-mentioned reference virus isolates. Lysates obtained from uninfected cells were used as a negative control. The ELISA plates coated with 300 ng of the lysates obtained as described were then left at 4°C overnight. The next day, after removal of the unbound antigen, the plates were washed 5 times with PBS, and the unspecific binding sites were blocked with 3% albumin in PBS for 1 hour at 37°C. After removal of the blocking solution, the supernatants of the cell cultures treated as described above and containing the soluble Fabs were added thereto, followed by an incubation step at 37°C for 2 hours. After 10 washing cycles with PBS/0.05% Tween 20, 40 μl of a 1:700 dilution of a polyclonal preparation of radish peroxidase-conjugated goat anti-human Fab immunoglobulins (Sigma) in PBS/1% BSA was added thereto. After a 1-hour incubation at 37°C and a further series of 10 washes, the substrate (OPD-o-phenylenediamine) was added to the wells. The plates were then incubated for 30 minutes at room temperature in the dark. The reaction was quenched with 1N sulfuric acid and the optical density was assessed by spectrophotometric reading at 450nm. All the assayed

clones displayed reactivity towards the lysates obtained from the infected cells. One bacterial clone transformed with an expression vector containing a gene pair encoding the light chain of a human antibody and the heavy chain Fd fragment was thus selected for each of the cross-reactive monoclonals. Such bacterial clones are able to produce human Fabs capable of binding both the isolate A/PR/8/34 (H1N1) and the isolate A/PC/1/73 (H3N2). These clones (with the relative gene pairs) were named INF4, INF16, INF28, INF39, INF43 and INF47.

6. Purification of the Fabs

The Fabs produced from the above-listed cross-reactive clones (from here on indifferently referred to as "clones" or "Fabs") were thus produced through bacteria transformed with the described expression vector and then immunoaffinity purified with columns composed of a sepharose resin containing the protein G (~ 2 mg/ml), to which a polyclonal preparation of goat antibodies capable of binding human Fabs (PIERCE, Illinois) was covalently linked. In short, a single colony of each clone was inoculated into 10 ml of SB medium containing ampicillin and tetracycline at 50μg/ml and 10μg/ml, respectively. The culture, which was grown overnight at 37°C, was sub-inoculated into a flask with 500 ml of SB added with the same concentration of antibiotics as before. The cells, subsequently induced by 1mM IPTG, were left shaking overnight at 30°C. The culture was centrifuged at 5000 rpm for 25 minutes and the pellet resuspended in PBS was sonicated. A further centrifugation at 18,000 rpm for 25 minutes was necessary in order to remove the cell debris. The supernatant was filtered, and then it was slowly passed through the above-described sepharose column. Thereafter, the resin was washed with 10 PBS volumes, and finally the bound Fabs were eluted with an acidic solution (elution buffer - H_2O/HCl pH 2,2). The various fractions collected were neutralized with an appropriate solution (1M Tris pH 9) and concentrated by ultrafiltration (Centricon, Millipore). The purity of the purified Fabs was assessed by running one aliquot on a 12% polyacrylamide/sodium dodecyl sulfate gel (SDS-PAGE). Finally, sequential dilutions of the purified Fabs were assayed by ELISA as described. Into each plate, preparations of monoclonal Fabs directed against HCV E2 glycoprotein were included as negative controls. The results of this experiment confirmed those

previously obtained with the bacterial lysates.

7. Immunofluorescence assessment of the monoclonal Fabs obtained by cloning into PCb3/CAF

In order to confirm the data achieved by ELISA, the cross-reactive anti-influenza Fabs were also analyzed by an immunofluorescence assay. Briefly, the cells from the infected cultures were trypsinized and, after two washes in PBS, counted under a microscope with a hematocytometer. The cell suspension was thus used for the preparation of slides by centrifugation in a cytocentrifuge (Cytospin4, Shandon Southern Products) at 90 g for 3 minutes. The so prepared slides each contained a total of 2×10^5 cells. Control slides were prepared similarly with uninfected cells. The cells were then fixed and permeabilized at room temperature with a methanol-acetone solution (used at the temperature of -20°C) for 10 minutes. After 3 washes in PBS, the cells were incubated with the different clones (100 µg/ml) for 30 minutes at 37°C in a humid chamber and subsequently washed three times in PBS. The cells were then incubated for 30 minutes at 37°C in the humid chamber in the dark with a fluoresceine isothiocyanate-conjugated goat Fab (Sigma) diluted 1:200 in Evans Blue. The slides were examined under a fluorescence microscope (Olympus). A commercial mouse monoclonal (Argene) specific for the M1 influenza virus protein was used as a positive control. An antibody directed against the E2 glycoprotein of the hepatitis C virus (e509; Burioni et al, Hepatology, 1998) was used as a negative control. All the recombinant Fabs showed, by immunofluorescence, a reactivity that was specific for both the cells infected with the strain A/PR/8/34 (H1N1) and those infected with the strain A/PC/1/73 (H3N2). Instead, no fluorescence was seen in uninfected cells, B type strain-infected cells, or cells infected with the negative control antibody.

8. Neutralization assay

In order to characterize the *in vitro* biological activity of the selected clones, neutralization assays were designed for the three reference virus isolates used in the study. In short, MDCK cells were seeded into MEM-10% FBS in a 96-well plate (2×10^4 cells/well). Serial

dilutions (from 10^{-1} to 10^{-8}) of the virus stocks, obtained as described above, were prepared in maintenance medium (MEM with 2% FBS). Each dilution was repeated six times. When the cultured cells were confluent, the growth medium was removed and 100 µl of each of the virus dilutions were added to each well. After 1 hour at 37°C, the inocula were removed and 200 µl of MEM medium added with 1 µg/ml trypsin were placed into each well. The viral titer, expressed as $TCID_{50}$ (the dose that infects 50% of the cell culture), was calculated by applying Reed-Muench's formula:

$$TCID_{50} = \frac{\text{infectivity} > 50\% - 50\%}{\text{infectivity} > 50\% - \text{infectivity} < 50\%} \times \text{dilution factor}$$

In the light of the obtained data, the virus stock was diluted so as to use a multiplicity of infection (M.O.I.) of approximately 0.01 (1 virus particle per 100 cells) in the neutralization experiment. In the actual neutralization assay, MDCK cells were seeded in a 24-well plate, with each well containing a sterile slide. The neutralization experiment was performed on 80%-90% confluent cells, i.e. about 48 hours after the seeding thereof. Dilutions of the purified Fab fragments were then prepared, so as to attain 2.5 µg/ml, 5 µg/ml, 10µg/ml and 20 µg/ml final concentrations for each antibody. Corresponding dilutions of the e509 anti-HCV antibody were prepared as a negative control. The various Fab concentrations were then incubated with the same volume of diluted virus stock (M.O.I.: 0.01) for 1 hour at 37°C. 250 µl of the virus-Fab mix were subsequently added to the wells containing the cells. A positive control for the infection was achieved by adding the culture medium alone to the virus stock. The plate was incubated for 1 hour at 37°C in order to allow the non-neutralized virus to adsorb. The inoculum was then removed and the cells were washed twice with PBS. 1.5 ml of serum-free medium with 1 µg/ml trypsin were added to each well. After a 6-hour incubation at 37°C, the cell monolayer was washed with PBS and fixed with a cold methanol-acetone solution (1:2 ratio, stored at -20°C) for 10 minutes at room temperature. The fixed cells were washed and incubated with 250 µl of a commercial monoclonal anti-M1 antibody (Argene) for 30 minutes at 37°C in a humid chamber. The cells were washed with PBS and finally incubated with a fluoresceine-conjugated goat anti-mouse antibody, diluted in Evans blue, for 30 minutes at 37°C in a humid chamber in the

dark. After three washes in PBS, the slides were finally examined under a fluorescence microscope. The Fabs' neutralizing activity was determined by counting the single positive cells and calculating the percentage decrease in the number of infected cells, compared to the positive control infected with the virus alone. The neutralization assays were carried out in three separate sessions for each Fab. Particularly, each clone was assayed against the two different reference type A influenza strains and the reference type B strain mentioned previously. In each experiment, the different Fab dilutions were repeated in triplicate, similarly to what performed for the negative (Fab e509 anti-E2/HCV) and positive (virus and medium without Fabs) controls of infection.

Among the six assayed cross-reactive Fabs, the Fab produced by clone INF28 showed a heterotype cross-neutralizing activity against the type A virus isolates. Instead, no reduction was detected with regard to the infecting ability of type B virus used in the study, confirming the specificity of the neutralizing activity observed. In particular, the Fab produced by clone INF28 (called Fab 28) showed an IC_{50} (the Fab concentration that inhibits 50% of infection by the virus isolate assayed) below 5 μg/ml in the case of subtype H1N1 and of approximately 10 μg/ml in the case of subtype H3N2, i.e. concentrations that are easily obtainable by an *in vivo* administration of the molecules in question even without taking into account the considerable increase in the neutralizing biological activity usually observed when Fabs are converted into the whole immunoglobulin form, one of the possible pharmaceutical formulations included within the scope of the invention.

Figures 1 to 3 summarize the results obtained with Fab 28, produced by clone INF28, in the different neutralization sessions performed on the various influenza virus isolates used in the study. Particularly, Figure 1 is a graph that illustrates the neutralization percentage of the virus A/PR/8/34 (H1N1) by different Fab 28 concentrations. The results obtained with the human e509 anti-HCV Fab are reported as a negative control. Figure 2 is a graph that illustrates the neutralization percentage of the virus A/PC/1/73 (H3N2) by different Fab 28 concentrations. The results obtained with the human e509 anti-HCV Fab are reported as a negative control. Figure 3 is a graph that illustrates the neutralization percentage of the virus B/Lee/40 by different Fab 28 concentrations. The results obtained with the human e509

anti-HCV Fab are reported as a negative control.

9. Characterization of the antigen recognized by Fab 28: Western blot on a lysate from infected cells

10 µg of a cell lysate infected with strain A/PR/8/34 (H1N1), prepared as described earlier, were run under native conditions on a 10% polyacrylamide gel. For this purpose, the samples were run at 100V for 1 hour in a proper refrigerated tank (BIORAD). Thereafter, the gel was removed from the electrophoresis apparatus and incubated for 10 minutes in Transfer Buffer (Tris base 3g; Glycine 14.41 g, dH_2O 800 ml, Methanol 200 ml) in order to eliminate any detergent residue. The transfer onto a nitrocellulose membrane (Hybond-ECL; Amersham Biosciences) was then carried out overnight at 30V and 90mA. The membrane was then blocked for 1 hour with 5% dried milk dissolved in 1X PBS and thereafter washed three times in 1X PBS – 0.1% Tween. During each wash, the membrane was left shaking on a swinging platform for 10 minutes. After which, the different Fabs, diluted in PBS with 5% dried milk, were added at the concentration of 5 µg/ml. Besides Fab 28, the following controls were added: e509 as a negative control; commercial mouse anti-HA whole IgG1 (COVANCE); commercial mouse anti-M1 whole IgG1 (ARGENE); mouse anti-M2 whole IgG1 (ABCAM); human serum diluted 1:200. Each antibody was left shaking for 1 hour at room temperature. Thereafter, the membrane was washed again in PBS as described earlier. The same secondary mouse (1:1000) or human (1:2000) antibodies as described for the ELISA assay were then added, depending on the source of the antibody to be detected. For the detection of the signal, a working solution was prepared by mixing two substrates (SuperSignal® West Pico Chemiluminescent Substrate Pierce) in a 1:1 ratio, being particularly careful not to expose it to sources of light. The nitrocellulose membrane was incubated for 5 minutes with the working solution and then removed and mounted in a HyperCassette (AMERSHAM). This was developed on a Kodak X-ray film in the dark room after the necessary exposure time. The described assay was performed in two different sessions, and in each of them the membrane portion incubated with Fab 28 showed the presence of a band weighing slightly less than 80 KDa, consistent with the weight of the immature form of the viral hemagglutinin (HA0). This was confirmed by the same band

being also displayed on the strip incubated with the anti-hemagglutinin control antibody. An analogous band, more intense than the others, was also detected in the membrane portion incubated with human serum. The result of this experiment shows that the antibody is directed against the influenza virus hemagglutinin, perfectly consistent with the neutralization data, since hemagglutinin is known to be the target of the immune neutralizing antibody response.

10. Neutralization assay by plaque reduction assay

Neutralization assays were carried out by using the plaque assay technique to assess more accurately the neutralizing activity of Fab 28. Firstly, preparations of virus isolates, subtypes H1N1 and H3N2, were quantified by plaque assay with the following protocol. MDCK cells were cultured in six-well plates (Costar) in MEM medium supplemented with penicillin and streptomycin (pen/strep), and enriched with 10% fetal bovine serum (FBS). After the cell monolayer had reached 100% confluence, the wells were washed with PBS and fresh MEM culture medium supplemented with the same antibiotics (pen/strep) and trypsin (1 μg/ml) was added thereto. Serial dilutions of the virus stocks were made in the same wells, and the virus was left to adsorb for 1 hour at 34°C under a 5% CO_2 atmosphere. The medium was then aspirated and two washes with PBS were done. More MEM supplemented with antibiotics, trypsin (1 μg/ml) and 0.8% agarose was gently added at a temperature not over 42°C. After infection, the health condition of the cell monolayer was checked under a phase contrast light microscope, and the plates were incubated at 34°C under a 5% CO_2 atmosphere. 48 hours after infection, the agarose layer was removed, being very careful not to damage the cell monolayer. Thereafter, 70% methanol in water, added with crystal violet (1% w/v), was added to the wells. The plate was incubated with permeabilizer/dye at room temperature for 5 minutes. After incubation, the plate was washed with distilled water at room temperature and left to dry under a laminar flow for 5 minutes. Finally, the PFU (plaque forming units) number was assessed under the phase contrast microscope at 4X magnitude. Once the virus titer had been calculated as PFU, the corresponding TCID50 were calculated, and that same titer was compared to the titer of the analogous virus stocks by the end-point limiting-dilution technique.

The above titration allowed for quantification of the viruses for the precise assessment of the activity of Fab 28. Several plates were set up analogously to the above-mentioned procedure for titration by plaque assay. A neutralization mix was thus prepared, which comprised the virus (100 TCID50 per well) and different concentrations of the Fabs that were used (Fab 28 and control Fab). In particular, the assay was performed by testing different concentrations of Fabs (20, 10, 5 and 2.5 μg/ml) against 100 $TCID_{50}$ of the diverse influenza virus strains. The virus/Fab mixtures were then incubated for 1 hour at 34°C under a 5% CO_2 atmosphere. After washing the MDCK cells with PBS, the pre-incubated preparations were transferred into the wells having a 100% confluent cell monolayer, then were incubated for 1 hour at 34°C under a 5% CO_2 atmosphere. The assay was carried out and interpreted as described previously, by comparing the number of plaques obtained in the presence of Fab 28 with those obtained in the presence of the same concentration of the control Fab.

The assays were performed using the following influenza isolates belonging to subtypes H1N1 and H3N2:

H1N1:

A/Malaya/302/54

A/PR/8/34

H3N2:

A/Aichi/68

A/Victoria/3/75

A/Port Chalmers/1/73

The results confirmed the neutralizing activity of Fab 28 towards the influenza viruses H1N1 A/Malaya/302/54 and A/PR/8/34, confirming as well IC_{50} values below 2.5 μg/ml. A heterosubtype neutralizing activity was also confirmed against the influenza viruses H3N2 A/Aichi/68, A/Victoria/3/75 and A/Port Chalmers/1/73 (IC_{50} approximately 20 μg/ml).

11. Identification of the epitope recognized by Fab 28

Several approaches were followed to identify the hemagglutinin region recognized by Fab 28, the ability of which to recognize an epitope, though conformational, had already been showed by previous experiments. Indeed, Fab 28 resulted capable of recognizing the protein only in Western blot assays performed under semi-native conditions (0.1% SDS). The same experiments had also pointed out the ability of Fab in recognizing only the immature form of the protein (HA0), but not the individual subunits (HA1 and HA2). Hemagglutination inhibition assays (HAI) had been carried out in parallel, with both chicken erythrocytes and human erythrocytes. Despite the remarkable neutralizing activity, Fab 28 proved to have no HAI activity, suggesting that it did not bind residues implicated in the binding between hemagglutinin and sialic acid.

For better characterization of the epitope, two complementary strategies were followed: selection of random peptide sequences, contained in a phage display library, which were able to bind the Fab 28 monoclonal; and *in vitro* induction, by selective pressure through Fab 28, of viral variants (escape mutants) capable of escaping the antibody's neutralizing activity.

Selection from the peptide library by the panning technique allowed for the identification of a number of peptides capable of specifically binding the Fab 28 idiotype. All the identified peptides were analyzed in order to generate a consensus sequence. Such a consensus sequence was then used for an *in silico* analysis of a hemagglutinin crystal belonging to subtype H1N1. By this analysis it was possible to reveal the regions potentially recognized by Fab 28. One epitope in particular was subjected to further analysis, in view of its compatibility with the results found earlier, and with those generated in parallel with the approach by the escape mutants. The epitope is localized on the stem region of hemagglutinin, that is in a portion between regions HA1 and HA2 (data perfectly consistent with the results achieved in the Western Blot and HAI assays). The residues critical for the binding which were identified are the following: W357 and T358 on region HA2; N336; I337; P338 on region HA1 (the numbering of the residues refers to the hemagglutinin sequence

from the isolate H1N1/A/PR/8/34 present in the BLAST database) (SEQ ID NO:5).

The assay by the escape mutants was carried out by serial infections of MDCK cells with 100 TCID50 of H1N1/A/PR/8/34 virus in the presence of 10 μg/ml of Fab 28, i.e. a Fab concentration equivalent to its IC90 against the isolate in question. Only after numerous passages, it was possible to detect infection of the cells in the presence of the Fab, indicative of a mutation occurred in the virus genome. In fact, escape mutants mutated in two residues of region HA2, I361 and D362, were selected, which are adjacent to the region identified by the *in silico* approach, confirming the hypothesis that this is the region recognized by Fab 28.

CLAIMS

1. A monoclonal antibody directed against the influenza A virus hemagglutinin antigen, characterized in that is capable of binding a plurality of subtypes of the influenza A virus.

2. A monoclonal antibody directed against the influenza A virus, characterized in that it has a neutralizing activity against a plurality of subtypes of the influenza A virus.

3. A monoclonal antibody according to claim 1 or 2, wherein the said plurality of subtypes of the influenza A virus comprises at least one influenza A virus subtype containing hemagglutinin H1 and one influenza A virus subtype containing hemagglutinin H3.

4. A monoclonal antibody according to claim 2 or 3, comprising at least one heavy chain variable domain and one light chain variable domain, with the heavy chain variable domain having amino acid sequence SEQ ID NO:1 and the light chain variable domain having amino acid sequence SEQ ID NO:2.

5. The monoclonal antibody according to claim 4, comprising at least one heavy chain variable domain and one light chain variable domain, with the heavy chain variable domain encoded by nucleotide sequence SEQ ID NO:3 and the light chain variable domain encoded by nucleotide sequence SEQ ID NO:4.

6. The monoclonal antibody according to claim 1, which is capable of binding the hemagglutinin conformational epitope specifically recognized by the monoclonal antibody according to claim 5.

7. A monoclonal antibody according to any of claims 1 to 6, selected from the group consisting of whole immunoglobulins and immunoglobulin fragments comprising at least one heavy chain variable domain and one light chain variable domain.

8. The monoclonal antibody according to claim 7, wherein the said immunoglobulin

fragments are selected from the group comprising Fab fragments, Fab' fragments, $F(ab')_2$ fragments, Fv fragments, single chain antibodies (scFv).

9. A monoclonal antibody according to any of claims 1 to 8, which is a human or humanized antibody.

10. An isolated polypeptide selected from SEQ ID NO:1 and SEQ ID NO:2, or fragment thereof at least 8 amino acids in length capable of binding a plurality of subtypes of the influenza A virus *in vitro*.

11. The isolated polypeptide according to claim 10, which has a neutralizing activity against a plurality of subtypes of the influenza A virus.

12. An anti-idiotype antibody that is specifically directed against the idiotype of a monoclonal antibody according to any of claims 1 to 9.

13. An isolated nucleotide sequence selected from SEQ ID NO:3 and SEQ ID NO:4.

14. An expression vector comprising nucleotide sequence SEQ ID NO:3, or nucleotide sequence SEQ ID NO:4, or both the nucleotide sequences SEQ ID NO:3 and SEQ ID NO:4.

15. A host cell transformed by an expression vector according to claim 14.

16. A pharmaceutical composition comprising an effective amount of at least one antibody or one polypeptide according to any of claims 10 to 12 and a pharmaceutically acceptable carrier and/or diluent.

17. An antibody or polypeptide according to any of claims 1 to 12, as a prophylactic or therapeutic medicament for an influenza A virus infection or a pathology directly or indirectly caused by an influenza A virus infection.

18. The use of an antibody or polypeptide according to any of claims 1 to 12 for the manufacture of a prophylactic or therapeutic medicament for an influenza A virus infection or a pathology directly or indirectly caused by an influenza A virus infection.

19. The use according to claim 18, wherein the pathology caused by an influenza A virus infection is the influenza syndrome.

20. An assay method for detecting, in a biological sample from a patient, the presence of anti-influenza virus antibodies having a heterosubtype cross-neutralizing property, comprising contacting the said biological sample with a monoclonal antibody according to any of claims 1 to 9 as a specific assay reagent.

21. A diagnostic kit comprising a monoclonal antibody according to any of claims 1 to 9 as a specific reagent, the said kit being particularly designed for use in a method for detecting or quantifying anti-influenza A virus antibodies having a heterosubtype cross-neutralizing property in a biological sample obtained from a patient.

22. An assay method for detecting, in an immunogenic or vaccine composition, the presence of influenza A virus epitopes capable of eliciting anti-influenza A virus antibodies having a heterosubtype cross-neutralizing property against the influenza A virus, in a subject to which it is administered, comprising contacting the said composition with a monoclonal antibody according to any of claims 1 to 9 as a specific assay reagent.

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