Revising the Chromosome-Specific Probes of White Hawk (Leucopternis albicollis) †

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Abstract: Leucopternis albicollis is a diurnal bird of prey with extensive karyotype reorganization. Chromosome-specific probes from this species have been used successfully to detect intrachromosomal rearrangements in different species of bird since 2010. However, some gaps were detected in this first set of probes. Here, we have obtained a new set of whole chromosome probes in order to improve the previous one; also, we have performed experiments using bacterial artificial chromosome (BAC) from chicken microchromosomes. Our results demonstrated that the microchromosomes were involved in fusion events. In addition, a new nomenclature has been proposed for the new set of probes and some inaccurate data were corrected.

Keywords: flow karyotype, microchromosomes, fusions, nomenclature

1. Introduction

Whole chromosome probes have provided the opportunity to analyze the chromosome homology, organization and evolution of different taxa with more accuracy than methods based on conventional banding techniques. The first avian set of chromosome paints was obtained from Gallus gallus (chicken—GGA) and has become a powerful tool to detect chromosome rearrangements and chromosome signatures between different species, facilitating the proposal of phylogenetic inferences [1,2]. However, considering that most species of birds have retained karyotypes similar to G. gallus, with maintenance of most syntenic groups, the application of GGA paints is not able to detect intrachromosomal rearrangements, such as inversions, apart the few cases in which chromosome fusions occurred previously to the inversion events, such as in some Psitaciformes [3].
An alternative approach to the limitations of *G. gallus* probes was the use of whole chromosome paints obtained from a species in which syntenic groups have been fissioned or reshuffled, such as the white hawk (*Leucopternis albicollis*) [4]. Despite having a diploid number of 2n = 66, the ancestral macrochromosomes 1–3 (GGA1-3) and 5 (GGA5) have been fissioned in *L. albicollis* [4]. For instance, from the sorted chromosomes of *L. albicollis*, five different pairs were assigned to GGA1. Hence, the use of these paintings allowed the detection of intrachromosomal rearrangements in species with the ancestral chromosome 1 conserved as an entire chromosome, such as in Columbiformes [5], or in species with fissions in this chromosome, such as in Passeriformes [6]. However, the fact that the five previously chromosomes of *L. albicollis* identified as homologous to GGA1 did not cover the entire chromosome 1 of Columbiformes raised the suspicions that at least one more chromosome of *L. albicollis* should be assigned to GGA1 [5]. Similar results were observed in Opisthocomiformes and Cuculiformes [7,8]. Hence, the aim of this study was to generate a new set of chromosome paints of *L. albicollis* in order to obtain a better coverage of GGA chromosomes. In addition, we performed fluorescence in situ hybridization (ISH) using bacterial artificial chromosomes (BACs) of *G. gallus* microchromosomes in order to demonstrate which microchromosome pairs were involved in fusions, which played an important role in the karyotype evolution of *L. albicollis*.

2. Material and Methods

2.1. Flow Sorting

Flow sorting was performed according to Nie et al. [9]. Chromosome preparations were obtained from a fibroblast cell line of a female *Leucopternis albicollis*. Chromosomes were stained with chromomycin A3 (40 µg/mL) and Hoechst 33,258 (2 µg/mL) (Sigma Aldrich, St. Louis, MO, USA). Sorting was carried out using a dual-laser cell sorter (MoFlo, Beckman Coulter, Brea, CA, USA). The primary sorted chromosome material was amplified by degenerate oligonucleotide-primed polymerase chain reaction (DOP-PCR) [10] and then resulting products were labeled with biotin-16-dUTP during secondary DOP-PCR amplification. The identity of probes was validated by same-species chromosome painting.

2.2. Chicken BAC Clones and Hybridization In Situ

Generation, labeling and experiments using bacterial artificial chromosomes (BACs) followed O’Connor et al. [11]. BACs were selected from the genome library of *Gallus gallus* (GGA). The slides were analyzed with an Olympus BX-61 epifluorescence microscope equipped with a cooled charge coupled device (CCD) camera and appropriate filters. Images were captured using SmartCapture3 (Digital Scientific, Cambridgeshire, UK).

3. Results

3.1. Flow Karyotype

The 66 chromosomes of *L. albicollis* were resolved into 33 peaks by flow cytometry (Figure 1). The chromosomes in each peak of the flow karyotype were identified on *L. albicollis* metaphases using fluorescent in situ hybridization (FISH) with labeled peak-specific DNA (Figure 2).
Figure 1. New flow karyotype of *L. albicollis*. Legend: M = Microchromosomes.

Figure 2. Representative same-species FISH experiments using *L. albicollis* (LAL) probes: LAL 4 (A), LAL8 (B) and cross-species LAL probes on *G.gallus* metaphases (C and D).
3.2. BAC-FISH Mapped onto L. albicollis Chromosomes

BAC probes corresponding to GGA chromosome pairs 17–28, except pair 20 (which did not produce reproducible results) demonstrated that all the microchromosomes were involved in fusion events on karyotype of L. albicollis.

3.3. Chromosome Painting between L. albicollis and Gallus gallus

Reciprocal chromosome painting between L. albicollis and G. gallus established chromosome homologies between these species, which are summarized in the Figure 3. The GGA1 was formally represented by five different pairs of L. albicollis (Figure 3A) [4]; however, in our analysis we found two extra small pairs, summing seven chromosomes of white hawk covering GGA1 (Figure 3B).

![Figure 3](image.png)

**Figure 3.** Homology map between chicken macrochromosomes and white hawk paints. (A) The homology described by de Oliveira et al. [4] (B) The new nomenclature has been proposed for the new set of probes from white hawk.

4. Discussion

In this study we provided a new set of whole chromosome probes from L. albicollis obtained by flow cytometry, which contributed to the improving the previously set one [4]. Specifically, we provided here the isolation and identification of some chromosomes which were missing in the first set. For instance, it has been proposed that five chromosomes of L. albicollis were homologous to chromosome 1 of Gallus gallus [1]; however, here we confirmed that are seven pairs of L. albicollis homologous to GGA1. These two small chromosomes, identified as pairs 22 and 26 (Figure 3), were not sorted as individual paints in the previous description, making it difficult to assign them in the homology map.

L. albicollis probes have been used in cytogenetics studies of birds since 2010, and intrachromosomal rearrangements were proposed in the chromosome homologous to GGA1 in some species, especially in Passeriformes and Columbiformes [5,6]. Although these studies have applied only five whole chromosome pairs of L. albicollis as homologous to GGA1, the occurrence of intrachromosomal rearrangements is still valid; however, the use of the two additional chromosomes identified herein as homologous to GGA1 (LAL 22 and LAL 25) (Figures 2 and 3) are involved in the rearrangements proposed or are conserved as an entire segments in species of Passeriformes and Columbiformes. Hence, intrachromosomal...
rearrangements proposed in Passeriformes and Columbiformes [5,6], may represent an even more complex series of inversions than initially proposed.

Considering that L. albicollis has 66 chromosomes, despite the occurrence of innumerable fission events in macrochromosomes, and a few pairs of microchromosomes, raised the idea that fusions involving these small elements were important in the karyotypic evolution of this species [4]. Hence, we confirmed this assumption and identified chromosome fusions involving GGA microchromosomes 17–28 (except 20—see materials and methods). Chromosome fusions involving microchromosomes have been previously detected only in Falconiformes and Psitaciformes [11].

As a conclusion, our results have improved the set of L. albicollis probes for comparative chromosome painting in birds and identified the homologous to GGA microchromosomes involved in fusions in the karyotype of the L. albicollis, by the use of BAC-derived probes.

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