CROATIAN MEDICAL JOURNAL
CMJ

45(4):434-444,2004

FORUM: ORIGIN OF MEDIEVAL CROATS

Craniometric Relationships among Medieval Central European Populations: Implications for Croat Migration and Expansion

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Aim. To determine the ethnic composition of the early medieval Croats, the location from which they migrated to the east coast of the Adriatic, and to separate early medieval Croats from Bijelo brdo culture members, using principal components analysis and discriminant function analysis of craniometric data from Central and South-east European medieval archaeological sites.

Methods. Mean male values for 8 cranial measurements from 39 European and 5 Iranian sites were analyzed by principal components analysis. Raw data for 17 cranial measurements for 103 female and 112 male skulls were used to develop discriminant functions.

Results. The scatter-plot of the analyzed sites on the first 2 principal components showed a pattern of intergroup relationships consistent with geographical and archaeological information not included in the data set. The first 2 principal components separated the sites into 4 distinct clusters: Avaroslav sites west of the Danube, Avaroslav sites east of the Danube, Bijelo brdo sites, and Polish sites. All early medieval Croat sites were located in the cluster of Polish sites. Two discriminant functions successfully differentiated between early medieval Croats and Bijelo brdo members. Overall accuracies were high – 89.3% for males, and 97.1% for females.

Conclusion. Early medieval Croats seem to be of Slavic ancestry, and at one time shared a common homeland with medieval Poles. Application of unstandardized discriminant function coefficients to unclassified crania from 18 sites showed an expansion of early medieval Croats into continental Croatia during the 10th to 13th century.

Key words: *craniometry; Croatia; multivariate analyses*

A key goal of physical anthropology is to analyze and document the vast range of human variability of past and present populations and to investigate the evolutionary and environmental forces responsible for phenotypic variation. So far, patterns of human variation among different geographical populations have been analyzed with genetic markers (1-2), linguistics (3), and skeletal data (4 6). Because skeletal morphology is determined by both genetic and environmental factors, some researchers have questioned the usefulness of skeletal data as the heritability of skeletal phenotypes is not known. However, numerous studies (7 10) have shown that skeletal data are both quantitatively and qualitatively comparable to genetic data. Anthropometric and craniometrical data have been successfully used to address questions of evolutionary history (11), as well as to infer historical relationships and document population movement and residence patterns of archaeological populations (4,12 14). The basic principle of these analyses is that morphological and metric (phenotypic) similarity reflects genetic similarity.

Craniometrical analyses are particularly amenable to answering questions related to the origin of the first Croat populations that settled on the east coast of the Adriatic. The reason for this is that available historical sources regarding both the origin of, and the time of arrival of the first Croatian populations on the east Adriatic coast, are inconsistent and vague (15). Two similar, but slightly differing reports are presented in the "*De Administrando Imperio*", written in the 10th century by the Byzantine Emperor Constantine VII (16). In the 29th and 31st chapters of this book, the Emperor stated that the Croats originated from an area north of Hungary and that the Byzantine Emperor Heraclius (610-641) invited them to live in Dalmatia. During their migration the Croats defeated the Avars who resided in modern continental Croatia and settled on the east Adriatic coast after which they were, again on the orders of Heraclius, christened by priests from Rome. The 30th chapter, written by an anonymous writer, gives a slightly different account and states that Croats originated from an area north of Bavaria where they were subject to the Franks. Led by five brothers (Klukas, Lonelos, Kosences, Muhlo, and Hrobatos), and two sisters (Tuga and Buga) they made their way south to Dalmatia which they settled after defeating the Avars. Following this, some Croats migrated north and settled in the former Roman provinces Illyria and Pannonia (modern continental Croatia and Hungary). Other medieval authors, writing in the 12th and 13th centuries disagree and state that Croats are of Germanic origin (15), one of them, Thomas the Archdeacon in his *"Historia Salonitana"* even equating the Croats with Goths (15).

Faced with these conflicting accounts, modern historians have developed several theories to explain the ethnic and geographical origin of the early medieval Croat population. Most historians believe that the Croats are of Slavic origin and that they migrated to the east Adriatic coast from an, as yet, unidentified location to the north of modern Croatia. Possible locations include Bavaria, southern Poland, and modern Slovenia. The Germanic theory has largely been abandoned because of clear historical errors regarding the time of arrival of the Goths in Dalmatia in Thomas the Archdeacon's writings (15). However, some historians believe that early medieval Croats are of Iranian origin. This theory is postulated on the basis of linguistic similarities between the Croatian name for Croats *"Hrvat"* and the Persian satrapy *"Harauvatiš"* mentioned in an inscription dated to the reign of the Persian king Darius, and on inscriptions recovered from the 3rd century AD Greek settlement in Tanais (modern Azov on the estuary of the river Don) which mention the names *"Horoatos"* and *"Horuatos"* (15). Therefore, some historians believe that early medieval Croats were originally an Iranian tribe that over time lost all of its Iranian attributes except for its Iranian name and some elements of Zoroastrism (17).

Historical source are also vague about the extent of the area occupied by the early medieval Croats and the relationship between the newly arrived Croats and the autochthonous Illyro-romanic population. Having survived attacks by both Franks and the Byzantine Empire in the 8th and 9th centuries, the Croats gradually strengthened their hold on the eastern Adriatic coast and began expanding northward into modern Bosnia and Herzegovina, and modern continental Croatia (18). By the 10th century the Croatian king Tomislav crossed the Dinaric Mountains and included the former Roman capital Siscia (modern Sisak approximately 60 km south of Zagreb) in his kingdom. This expansion was, however, fiercely contested by Hungarians and Bulgars and the 10th and 11th centuries in continental Croatia were characterized by anarchy with sovereignty changing between Hungary and Croatia (19).

To what degree population movements mirrored the frequent political changes in continental Croatia is not at present known. From the archaeological point of view, this period in continental Croatia is known as the Bijelo Brdo culture (20). This term had been used for over 70 years to designate different types of material remains with common characteristics recovered from medieval graves in Slovakia, Hungary, Slovenia, continental Croatia, Vojvodina, and western Romania. The name of the culture derives from the eponymous site near Osijek in Croatia. The bearers of the Bijelo Brdo culture have been identified as Slavs and Hungarians with the Slav component being very heterogeneous (20).

The aim of this investigation was to analyze craniometrical relationships between Central and South-east European medieval archaeological populations. Selected craniometrical data were analyzed with two multivariate statistical procedures: principal components analysis and discriminant functions. The primary objective of the principal components analysis was to determine, based on craniometrical similarities, the ethnic composition of the early medieval Croat population and, if possible, the location from which they migrated to the east coast of the Adriatic. The purpose of the discriminant function analysis was to develop functions that would separate early medieval Croats from their northern neighbors belonging to the Bijelo Brdo culture. This would allow us to document population movement by identifying early medieval Croat, Bijelo Brdo, or mixed settlements in Bosnia and Herzegovina and continental Croatia.

Methods

The data analyzed in this investigation were craniometrical measurements from males and females recovered from medieval cemetery burials in Central and South-east Europe. The only criteria for inclusion in the analysis were firm archaeological dating of the site, and the presence of measurable skulls. All sites used to generate discriminant functions dated from the 8th and 11th centuries. Sites included in the principal components analysis cover a slightly larger temporal span from the 4th to the 16th centuries, with the majority (28/39 or 72%) of sites dating from the 7th to 12th centuries. The 5 Iranian sites included in the analysis were older, from the 5th century B.C. to the 2nd century A.D., to coincide with the inscriptions from the Greek settlement in Tanais. These data were analyzed with two multivariate statistical procedures: principal components analysis (21) and discriminant functions (22).

Principal Components Analysis

Principal components analysis is a powerful exploratory technique that reduces the number of variables in a data set by finding linear combinations of those variables that explain most of the variability. This analysis is usually used for data reduction and de-correlation of the variables. In this investigation, however, principal components analysis was primarily used as an exploratory tool in the search for underlying patterns/structures of relationships between discrimination and association of medieval populations and corresponding specific skeletal features. A structure of relationships was considered stable when the clusters of sites produced by the analysis corresponded with geographical, archaeological, or historical information not included in the original data matrix.

Sample Used for Principal Components Analysis

The sites included in the principal components analysis are presented in Table 1. Craniometrical data from 39 European sites were available for analysis. Eight of the sites were located in modern Croatia, 1 in Slovenia, 2 in Bosnia and Herzegovina, 1 in Serbia and Montenegro, 18 in Hungary, 2 in the Czech Republic, 3 in Slovakia, 1 in Austria, and 3 in Poland. Because some historians believe early medieval Croats were of Iranian origin (17), 5 Iranian sites were also included in the analysis.

Craniometrical data from 4 sites in modern Croatia (Danilo, Stari Jankovci, Privlaka, and Bijelo brdo) were collected by the authors. The remaining data were obtained by numerous researchers and published in different journals (23–60). This precluded the use of raw measurements in the analysis as the majority of researchers reported only on the mean values of males for each measurement. Consequently, male mean values for 8 cra-

Table 1. European and Iranian archaeological sites that provided skulls in the principal component analysis

Site	Country	Century	Reference
European:			
1. Vukovar	Croatia	10-11	Pilarić and Schwidetzky (23)
2. Bribir	Croatia	9-11	Pilarić and Schwidetzky (23)
3. Mravinci	Croatia	9-10	Mikić (24)
4. Nin	Croatia	8-10	Štefančić (25)
5. Danilo	Croatia	10-16	Šlaus (26)
6. St. Jankovci	Croatia	7-8	Šlaus (27)
7. Privlaka	Croatia	8-9	Šlaus (27)
8. Bijelo Brdo	Croatia	10-11	Šlaus (28)
9. Bugojno	Bosnia and Herzegovina	10-16	Klug (29)
10. Gomjenica	Bosnia and Herzegovina	10-11	Pilarić (30)
11. Tokod	Hungary	4-5	Ery (31)
12. Baranya	Hungary	4-5	Ery (31)
13. Kékesd	Hungary	8	Wenger (32)
14. Kérpuszta	Hungary	10-12	Liptak (33)
15. Szekszárd-Palánk	Hungary	6-8	Liptak (34)
16. Toponár-Őrház	Hungary	8	Wenger (35)
17. Alattyán-Tulát	Hungary	6-8	Wenger (36)
18. Ártánd	Hungary	8	Ery (37)
19. Homokmégy	Hungary	7-8	Liptak (38)
20. Madaras	Hungary	6-8	Liptak and Marcsik (39)
21. Sükösd Ságod	Hungary	7	Kohegyi and Marcsik (40)
22. Szeged Fehértó A	Hungary	6-8	Liptak and Vamos (41)
23. Szeged Kundomb	Hungary	6-8	Liptak and Marcsik (42)
24. Szeged Makkos.	Hungary	6-8	Vamos (43)
25. Szentes Kaján	Hungary	7-8	Wenger (44)
26. Üllő I	Hungary	7-8	Liptak (45)
27. Üllő II	Hungary	7-8	Liptak (45)
28. Kecel I	Hungary	8	Liptak (46)
29. Virt	Slovakia	7-8	Hanakova et al (47)
30. Želovce	Slovakia	7-8	Stloukal and Hanakova (48)
31. Nové Zámky I+II	Slovakia	8	Stloukal and Hanakova (49)
32. Josefov	Czech Republic	9	Hanakova and Stloukal (50)
33. Mikulčice	Czech Republic	9	Stloukal and Vyhnanek (51)
34. Pitten	Austria	9	Fabrizii and Reuer (52)
35. Ptuj	Slovenia	10-11	Ivaniček (53)
36. Nadrljan-Salaš	Serbia and Montenegro	6-7	Bartucz and Farkas (54)
37. Cedynia	Poland	8-10	Wokroj (55)
38. Wišlica	Poland	10-13	Wiercinski (56)
39. Lednicki	Poland	9-12	Wokroj (57)
Iranian:			
1. Early Saka culture	Kazahstan	5-4 BC	Ginzburg and Trofimova (58)
2. Scythian culture	Russia	5-4 BC	Alekseev (59)
3. Sarmatian culture 1	Kazahstan	4 BC-2 AD	Ginzburg and Trofimova (58)
4. Sarmatian culture 2	Russia	4 BC-2 AD	Firshtein (60)
5. Sarmatian culture 3	Russia	4 BC-2 AD	Firshtein (60)

nial measurements were used in the principal components analysis. The use of mean values in principal components analysis is not uncommon, nor can inappropriate, but small sample size affect the scope and strength of the analysis (21). Therefore, sample sizes (minimum and maximum number of observations) are reported for each site included in the analysis.

Measurements Used in Principal Components Analysis

The 8 cranial measurements used in the principal components analysis were: maximum cranial length – Martin-Saller cranial measurement #1 (61), maximum cranial breadth – Martin-Saller #8, minimum frontal breadth – Martin-Saller #9, basion-bregma height – Martin-Saller #17, bizygomatic breadth – Martin-Saller #45, upper facial height – Martin-Saller #48, orbital breadth – Martin-Saller #51, and orbital height – Martin-Saller #52.

Mean male values for the 8 variables used in the principal components analysis are presented in Table 2. This table also lists the minimum and maximum number of measurements used to calculate the mean values of the craniometrical variables for each site.

Discriminant Function Analysis

Discriminant function analysis is used when data are classified into two or more groups and the researcher wishes to find one or more functions of quantitative measurements that will discriminate among the groups. The analysis has two main applications: analysis - interpretation of the ways in which the groups differ from each other; and classification - the procedure generates classification function coefficients that are used to assign new cases to groups on the basis of shared similarities. The new cases can belong to either a known, or an unknown group, thus allowing both testing of the accuracy with which the discriminant functions differentiate between the groups, and classification of ungrouped cases to known groups (22).

In this investigation a stepwise discriminant analysis was employed to select the best measurements for discrimination among the groups. Stepwise selection begins by entering the variable with the lowest Wilk's λ in the model. The variable that least contributes to the discriminatory power is removed from the model if it fails to meet the criterion to stay. Otherwise the variable that contributes the most to the discriminatory power that is not in the model is entered. The procedure stops when all variables meet the criterion to stay and no others can be entered.

In order to analyze the effectiveness of the functions, a "leave one out classification" technique was applied to the sample to measure the accuracy of multivariate classification. This jackknife approach takes one case aside and develops a discriminant function formula to classify that case. The process continues for all cases, one at a time.

If the discriminant functions could successfully discriminate early medieval Croats from members of the Bijelo Brdo culture, the unstandardized coefficients would be used for calculating discriminant function scores from measurements of skulls from archaeological sites in Slovakia, Hungary, Bosnia and Herzegovina, and continental Croatia not used in the discriminant function analysis. A discriminant score is obtained by multiplying each craniometrical variable with its unstandardized coefficient and

Table 2. Male mean values for cranial variables used in the principal components analysis

Site	Min/max No. obs.*	Mean male values for variables† 1	8	9	17	45	48	51	52
European:									
1. Vukovar	(42/91)	182.9	144.1	98.9	134.2	129.2	78.1	40.9	32.9
2. Bribir	(30/53)	185.8	135.1	98.1	136.5	119.0	67.7	40.0	32.9
3. Mravinci	(27/27)	186.1	138.3	97.9	136.3	131.3	68.9	38.1	30.3
4. Nin	(16/65)	187.7	138.1	96.7	135.4	131.3	70.3	40.7	32.9
5. Danilo	(14/21)	187.2	145.5	97.2	139.4	134.0	67.0	40.2	31.5
6. St. Jankovci	(14/23)	181.8	140.3	97.2	131.4	135.5	70.7	40.0	32.2
7. Privlaka	(20/37)	184.6	139.5	96.8	133.7	130.6	70.6	39.4	33.0
8. Bijelo Brdo	(21/37)	187.5	140.5	99.3	137.1	134.2	73.1	39.8	33.3
9. Bugojno	(29/45)	192.6	141.8	98.3	138.8	133.0	69.7	41.8	32.4
10. Gomjenica	(25/31)	190.9	138.7	97.7	139.3	128.8	71.3	39.7	33.5
11. Tokod	(17/38)	183.1	141.9	96.2	132.0	132.5	66.5	42.4	33.2
12. Baranya	(15/26)	184.5	140.9	97.0	132.5	130.9	70.1	42.2	34.2
13. Kékesd	(14/20)	182.9	143.7	99.4	137.3	134.3	69.8	41.8	33.8
14. Kérpuszta	(54/84)	183.4	142.6	99.1	135.1	133.7	69.3	36.3	32.6
15. Szekszárd-Palánk	(13/25)	184.1	146.1	99.3	137.1	134.7	70.7	40.5	33.1
16. Toponár-Őrház	(19/32)	188.0	140.3	98.3	137.7	132.9	69.3	42.1	33.7
17. Alattyán-Tulát	(47/110)	185.4	147.7	98.5	130.5	136.4	69.4	42.3	34.0
18. Ártánd	(12/35)	186.3	146.2	98.1	134.4	137.8	70.1	43.0	33.3
19. Homokmégy	(28/36)	181.9	145.2	97.4	133.2	134.3	72.2	40.3	33.1
20. Madaras	(16/18)	181.0	142.8	94.3	130.8	138.1	76.3	40.1	33.7
21. Sükösd-Ságod	(15/23)	182.9	141.8	95.7	127.8	133.1	69.5	40.8	32.8
22. Szeged Fehértó A	(44/79)	182.2	139.5	98.1	131.5	134.5	70.9	40.6	34.4
23. Szeged Kundomb	(39/64)	182.6	145.0	96.8	129.5	134.0	68.9	41.4	32.7
24. Szeged Makkos.	(18/33)	179.0	142.4	99.0	135.7	135.6	69.3	41.4	32.6
25. Szentes Kaján	(17/50)	178.2	143.1	97.6	136.2	134.0	70.7	40.6	33.8
26. Űllő I	(22/54)	181.8	143.8	95.4	130.3	132.6	71.6	39.7	32.7
27. Űllő II	(15/28)	181.5	144.8	98.1	129.9	134.2	69.9	39.3	31.6
28. Kecel I	(21/26)	181.8	145.4	98.2	129.6	134.6	70.6	40.0	32.8
29. Virt	(12/24)	184.1	140.4	98.7	136.4	130.5	68.2	41.9	32.5
30. Želovce	(26/65)	185.5	142.2	99.3	136.2	133.0	70.6	41.8	31.9
31. Nové Zámky I+II	(63/137)	184.5	140.1	97.8	133.1	134.3	71.5	41.0	33.3
32. Josefov	(12/15)	188.6	137.8	99.3	137.1	133.4	72.3	42.6	33.0
33. Mikulčice	(164/238)	187.4	142.6	99.2	137.0	133.9	72.4	41.9	33.7
34. Pitten	(11/23)	187.6	140.0	98.1	137.2	132.8	71.0	42.2	33.5
35. Ptuj	(49/89)	189.3	143.6	99.5	136.5	133.2	70.6	41.7	32.9
36. Nadrljan-Salaš	(17/32)	181.9	145.0	96.0	127.1	133.5	69.4	39.0	32.6
37. Cedynia	(64/86)	189.0	139.3	97.6	134.7	132.5	68.1	40.1	32.9
38. Wišlica	(18/33)	189.5	139.1	96.1	135.0	131.5	70.0	41.9	32.6
39. Lednicki	(294/360)	185.2	140.9	97.3	136.0	132.4	65.0	40.8	31.8
Iranian:									
1. Early Saka cult.	(20/31)	181.2	144.7	99.6	131.6	138.8	71.4	43.1	33.1
2. Scythian cult.	(12/17)	183.0	146.2	97.9	135.1	140.6	72.2	42.5	33.1
3. Sarmatian cult.1	(11/26)	185.6	145.9	99.6	132.7	138.2	71.5	44.2	33.2
4. Sarmatian cult.2	(43/82)	187.5	145.9	98.6	133.9	137.7	71.4	43.7	33.2
5. Sarmatian cult.3	(14/32)	185.0	147.5	99.2	132.5	138.7	71.9	43.7	32.9

*Minimum and maximum number of measurements used to calculate the mean values of the craniometric variables for each site.
†Variables defined by Martin and Saller (61): 1 – maximum cranial lenght; 8 – maximum cranial breadth; 9 – mimimum frontal breadth; 17 – basion-bregma height; 45 – bizygomatic breadth; 48 – upper facial height; 51 – orbital breadth; 52 – orbital height.

adding them together along with the constant (22). The discriminant score is then compared to the cut off point which is calculated by averaging the two group centroids. A value greater than the cut off point indicates an early medieval Croat, a lower value a member of the Bijelo Brdo culture. The 18 sites, with the number of male and female skulls selected for classification are presented in Table 3.

Sample Used in Discriminant Function Analysis

Raw data for 17 cranial measurements for 103 female and 112 male skulls were used in the analysis. The skulls were recovered from 6 sites, 5 from Croatia (4 from the east Adriatic coast, and 1 from continental Croatia) and one from Slovenia. All four east Adriatic coast sites are affiliated with early medieval Croats and are dated from the 8th to the 9th centuries. The two Bijelo brdo sites, the eponymous site Bijelo brdo and Ptuj in modern Slovenia, are dated to the 9th to 11th century. The number of skulls recovered from each site is presented in Table 4. All measurements were taken by the first author, except for measurements from the Ptuj cemetery which were taken by Ivaniček (53).

Measurements Used in Discriminant Function Analysis

The 17 cranial measurements used in the discriminant function analysis were: maximum cranial length – Martin-Saller #1 (61), cranial base length – Martin-Saller #5, maximum cranial breadth – Martin-Saller #8, minimum frontal breadth – Martin-Saller #9, basion-bregma height – Martin-Saller #17, frontal chord – Martin-Saller #29, parietal chord – Martin-Saller #30, occipital chord – Martin-Saller #31, basion-prosthion length – Martin-Saller #40, upper facial breadth – Martin-Saller #43, bizygomatic breadth – Martin-Saller #45, upper facial height – Martin-Saller #48, interorbital breadth – Martin-Saller #50, orbital breadth – Martin-Saller #51, orbital height – Martin-Saller #52, nasal breadth – Martin-Saller #54, and nasal height – Martin-Saller #55.

The multivariate statistics were performed using the Principal components and discriminant procedures of the statistical package SPSS 10.0 (SPSS Inc., Chicago, IL, USA).

Results

Principal Components Analysis

In the first analysis, only measurements from the 39 European sites were included in the data set. The procedure calculated 8 principal components to account for the total variability in the data set, the first two of which accounted for 52.9% of the variability in

Table 3. Number of crania from archaeological sites in Croatia, Bosnia and Herzegovina, Hungary, and Slovakia selected for classification by unstandardized coefficients developed by the discriminant functions

	No. of crania			
Site	male	female	Century	Reference
1. Nin	5	5	8-10	Štefančić (25)
2. Danilo	4	6	10-15	Šlaus (26)
3. Bribir	3	4	9-11	Pilarić and Schwidetzky (23)
4. Gomjenica	4	3	10-11	Pilarić (30)
5. Bugojno	4	6	10-16	Klug (29)
6. Ščitarjevo	2	3	10-12	Pintarić (62)
7. Đelekovec	9	4	12-13	Šlaus (63)
8. Lobor	3	3	11	Šlaus (63)
9. Zvonimirovo	2	2	11	Šlaus (63)
10. Josipovo	2	2	11	Boljunčić (64)
11. Đakovo 1	4	4	11-13	Šlaus and Filipec (6)
12. Vinkovci	3	3	11-13	Šlaus (28)
13. Vukovar	3	5	10-11	Pilarić and Schwidetzky (23)
14. Alsorajk	4	3	9	Ery (65)
15. Zalaszabar	4	9	9	Ery (66)
16. Garabonc	4	4	9	Ery (66)
17. Želovce	12	10	8	Stloukal and Hanakova (48)
18. Rajhrad	18	20	9	Hanakova et al (67)

Table 4. Early medieval Croat and Bijelo brdo sites which provided skulls used in the discriminant function analysis

Archaeological sites	No. of male crania	No. of female crania
Early medieval Croat:		
Šibenik	15	20
Radašinovci	11	14
Glavice	19	8
Dubravice	5	8
Bijelo brdo:		
Bijelo brdo	21	20
Ptuj	41	33
Total	112	103

the sample. The distribution of the sites on the first two principal components is shown in Figure 1. When the Croatian and Bosnian and Herzegovinian sites, whose relationships to the other sites are under analysis, were excluded from the picture (Fig. 2), the distribution showed a pattern of intergroup relationships consistent with geographical and archaeological information not included in the data set. The first principal component very accurately separated sites located west or north of the Danube from those located east of the Danube. The demarking point is at –0.6 on the first principal component. All sites with lower values on the first principal component were located east of the Danube, those with higher values, west or north of the Danube. The first two principal components also separated the sites into 4 distinct clusters. The first cluster consisted of Avaroslav sites west of the Danube, the second of Avaroslav sites east of the Danube, the third of Bijelo Brdo culture sites, and the fourth of Polish sites.

The positions of the analyzed Croatian sites in relation to the observed clusters were as follows. Sites from the east Adriatic coast: Nin, Bribir, Mravinci, and Danilo were located in the lower right part of the plot in the cluster of Polish sites. Nin, the most important early medieval Croatian site, occupied almost the same position as Cedynia, an early medieval site from northern Poland. The two Croatian Avaroslav sites: Privlaka and Stari Jankovci were located in the cluster of Avaroslav sites west of the Danube. Bijelo Brdo was located in the cluster of Bijelo Brdo sites, while

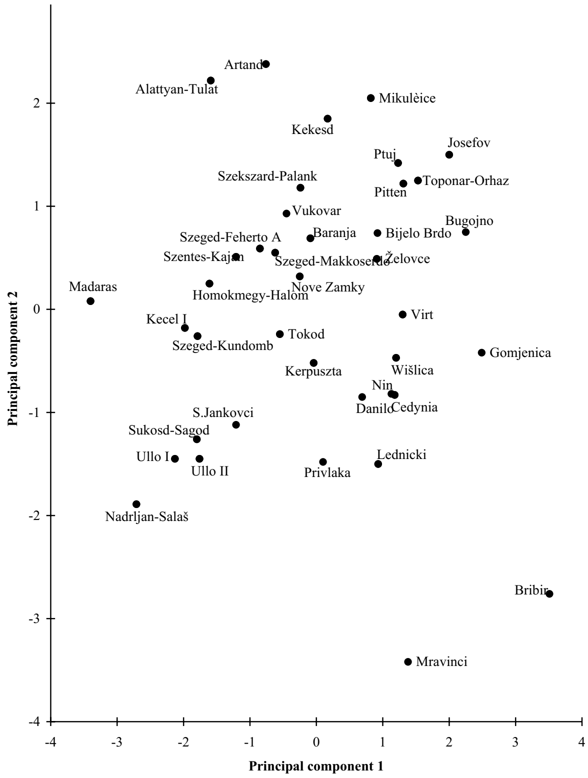

Figure 1. Scatter–plot of the 39 analyzed European sites on the first two principal components. The first two principal components account for 52.9% of the variability in the sample.

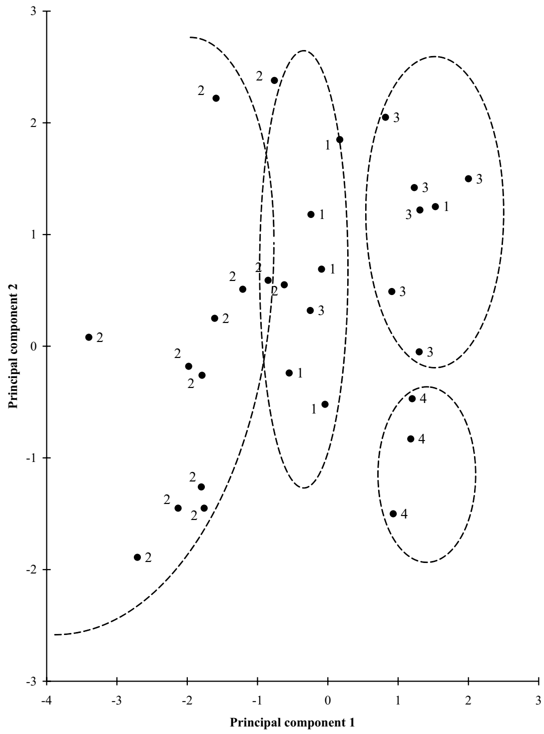

Figure 2. Distribution of the European sites on the first two principal components without Croatian and Bosnian sites. **1.** Avaroslav sites west of the Danube; **2.** Avaroslav sites east of the Danube; **3.** Bijelo brdo culture sites; **4.** Polish sites. Borders around the four groups were drawn to highlight the separation among the clusters.

Vukovar, another Bijelo Brdo culture site, appeared to be more similar to Avaroslav sites east of the Danube.

A second principal components analysis was also performed. In this analysis, data from the 5 Iranian sites was added to the 39 European sites. The results conclusively showed that the Iranian sites exhibited no similarities with the early medieval Croatian sites. The 5 Iranian sites showed little dispersion along the two axes and exhibited values from –1.0 to –2.1 on the first principal component, and from 2.2 to 3.4 on the second principal component. All of these sites would, therefore, have been located in the upper left-hand corner of Figure 1. Of all the European sites included in the analysis only two: Artand and Alattyan Tulat, both Avaroslav sites located east of the Danube, showed any similarity with the Iranian sites.

Values for the component weights in the first two principal components indicated that the first principal component was dominated by measurements defining the neurocranium (maximum cranial length, maximum cranial breadth, and basion-bregma height) and primarily differentiated between dolichocranic and brachycranic, and hypsicranic and chamaecranic skulls. Measurements defining the face were better represented in the second principal component which primarily differentiated between skulls with wide faces and large orbits, and skulls with narrow faces and small orbits (data not shown).

Discriminant Function Analysis

The results of the principal components analysis showed that early medieval Croat series exhibited marked similarities with Polish series, and no similarities with Iranian series. The analysis also suggested that considerable differences existed between the early medieval Croat sites: Nin, Danilo, Mravinci, and Bribir; and Bijelo Brdo culture sites such as Bijelo Brdo, Pitten, Ptuj, Josefov, and Mikulčice. The second principal component, with its high loadings for variables defining the facial region, seemed to differentiate between the two groups quite well. All of the early medieval Croat sites had negative values on the second principal component (Bribir and Mravinci had the lowest values of all the analyzed sites) while all Bijelo Brdo sites had positive values (Fig. 1).

To differentiate between the two groups, raw data for 17 cranial measurements for 103 female (50 early medieval Croat and 53 Bijelo Brdo), and 112 male (50 early medieval Croat and 62 Bijelo Brdo) skulls were subjected to stepwise discriminant function analysis. Descriptive statistics listing the means, standard deviations and univariate F–ratios for early medieval Croat and Bijelo Brdo males and females are presented in Table 5. The F–ratios indicated that differences between the two groups were statistically significant for six variables in both sexes. In both sexes the most significant differences were noted in interorbital breadth, followed by the variables orbital breadth and basion bregma height in males, and maximum cranial breadth and upper facial height in females.

Stepwise discriminant function analysis for males selected 7 of the 17 cranial variables. Interorbital breadth was chosen first, followed by upper facial breadth, basion bregma height, orbital breadth, bizygomatic breadth, maximum cranial breadth, and frontal chord. Seven variables were also selected for females. Interorbital breadth was again chosen first, followed by maximum cranial breadth, upper facial height, basion prosthion length, nasal height, minimum frontal breadth and cranial base length.

Standardized and unstandardized coefficients, group centroids, and sectioning points are presented in Table 6. Standardized coefficients indicated the relative contribution of each variable to the function. In males, interorbital breadth made the greatest contribution to the function, followed by upper facial breadth and bizygomatic breadth. Maximum cranial breadth and frontal chord contributed the least. In females, upper facial height, interorbital breadth and basion prosthion length made the greatest contributions to the function, while minimum frontal breadth and cranial base length contributed the least.

Table 5. Means, standard deviations and univariate F-ratios for variables used in the discriminant function analysis for early medieval Croat and Bijelo brdo males and females

	Early medieval Croat		Bijelo brdo		F-ratio	
Variable (mm)	males (n=50)	females (n= 50)	males (n=62)	females (n=53)	males	females
Maximum cranial length	191.8±5.96	180.6±5.67	189.1±5.26	179.5±6.28	6.67*	0.82
Cranial base length	105.3±6.71	98.1±3.91	104.3±4.99	97.4±4.39	0.76	0.65
Maximum cranial breadth	140.3±4.38	133.7±4.10	142.7±5.63	140.4±5.17	6.53*	52.62‡
Minimum frontal breadth	98.0±3.98	95.8±4.25	98.6±4.47	96.5±4.57	0.63	0.66
Basion-bregma height	140.3±5.81	131.9±3.96	137.2±5.46	129.7±5.72	8.78†	5.11*
Frontal chord	115.7±4.87	109.7±5.09	113.9±4.67	109.6±4.72	4.03*	0.01
Parietal chord	117.5±7.76	111.3±4.20	116.4±6.08	111.4±5.79	0.80	0.03
Occipital chord	100.9±5.10	97.0±3.60	99.7±6.47	95.8±5.65	1.17	1.45
Basion-prosthion length	98.2±6.74	91.3±4.84	98.9±6.70	92.4±4.79	0.33	1.23
Upper facial breadth	105.6±4.42	103.1±4.39	106.8±3.96	103.1±3.59	2.30	0.01
Bizygomatic breadth	134.4±4.82	123.9±4.93	132.8±5.59	126.6±4.91	2.50	7.43†
Upper facial height	71.9±4.53	68.4±3.44	70.7±4.67	63.6±3.31	2.27	50.76‡
Interorbital breadth	25.5±2.78	24.7±2.23	21.1±2.54	20.4±2.13	73.41‡	103.13‡
Orbital breadth	39.6±1.99	38.6±1.54	41.3±2.10	40.0±2.17	18.04‡	14.09‡
Orbital height	32.9±1.64	32.6±2.31	32.6±2.46	32.7±1.85	0.44	0.05
Nasal breadth	25.2±2.13	24.3±1.47	24.7±1.69	23.8±1.45	2.10	2.91
Nasal height	53.1±3.27	49.0±2.36	53.1±3.19	48.8±2.58	0.02	0.18

*Significant at $p<0.05$.
†Significant at $p<0.01$.
‡Significant at $p<0.001$.

Table 6. Standardized and unstandardized discriminant function coefficients, and group centroids for early medieval Croat and Bijelo brdo males and females

Variables in function	Standardized coefficient*	Unstandardized coefficient†	Group centroids
Males:			
Interorbital breadth	0.872	0.329	
Upper facial breadth	-0.771	-0.185	
Basion-bregma height	0.420	0.075	
Orbital breadth	-0.426	-0.207	Medieval Croat=1.491
Bizygomatic breadth	0.524	0.100	Bijelo b.=-1.202
Maximum cranial breadth	-0.377	-0.074	
Frontal chord	0.337	0.071	
Constant		-0.870	
Cut-off point		0.145	
Females:			
Interorbital breadth	0.879	0.403	
Maximum cranial breadth	-0.623	-0.133	
Upper facial height	1.019	0.302	
Basion-prosthion l.	-0.648	-0.135	Medieval Croat=2.224
Nasal height	-0.469	-0.189	Bijelo b.=-2.098
Minimum frontal breadth	-0.436	-0.099	
Cranial base length	0.431	0.104	
Constant		10.242	
Cut-off point		0.063	

*The standardized coefficient indicates how much a variable contributes to the overall classification.
†Unstandardized coefficients are used to calculate discriminant function scores from raw data. A discriminant score is obtained by multiplying each craniometric variable with its unstandardized coefficient, and adding them together along with the constant. The discriminant score is then compared to the cut-off point which is calculated by averaging the two group centroids. For instance, for males, a value greater than 0.1445 indicates an early medieval Croat, a lower value a member of the Bijelo brdo culture.

Table 7. Classification accuracies of the discriminant function for males and females

Discriminant function	No.* (%)†		
	Medieval Croat	Bijelo brdo	total
Reclassified:			
males	48/50 (96.0)	56/62 (90.3)	104/112 (92.9)
females	49/50 (98.0)	52/53 (98.1)	101/103 (98.1)
Cross-validated:			
males	46/50 (92.0)	54/62 (87.1)	100/112 (89.3)
females	49/50 (98.0)	51/53 (96.2)	100/103 (97.1)

*Number of crania correctly classified/number of crania analyzed.
†Percentage of crania correctly classified.

Reclassification of the cases used to develop the functions showed high overall accuracies (Table 7). The overall accuracy for males was 92.9%, for females even higher – 98.1%. The same table also shows cross validation percentages after using the leave one out classification. The results were very similar – 89.3% accuracy for males, and 97.1% accuracy for females.

Applying the unstandardized coefficient classification coefficients (Table 6) to the 18 sites from Slovakia, Hungary, Bosnia and Herzegovina, and continental Croatia not included in the discriminant function analysis gave the following results. Eight of the sites (Nin, Danilo, Bribir, Gomjenica, Bugojno, Ščitarjevo, Josipovo, and Vinkovci) were classified as early medieval Croat, 6 (Lobor, Zvonimirovo, Vukovar, Zalaszabar, Garabonc, and Rajhrad) as Bijelo brdo, and 4 (Đelekovec, Đakovo 1, Alsorajk, and Želovce) as mixed early medieval Croat and Bijelo Brdo sites. When these sites were separated into 2 temporal groups, an older group comprised of sites dating from the 8th to the 10th centuries, and a younger group comprised of sites dating from the 11th to the 13th centuries, and sites used to generate the discriminant functions were added, the following pictures appeared. Figure 3A shows the geographical locations of the older sites. As can be seen, all of the early medieval Croat sites were located on the east Adriatic cost. To the north, 3 Bijelo Brdo and 2 mixed Bijelo Brdo and early medieval Croat sites were located in modern Hungary and Slovakia.

Figure 3B shows the geographical positions of the younger sites. This is a more complex picture that appears to depict an expansion of the early medieval Croats into modern Bosnia and Herzegovina, and continental Croatia. Both of the sites from Bosnia and Herzegovina were classified as early medieval Croat. Of the 8 sites (Ščitarjevo, Lobor, Đelekovec, Zvonimirovo, Josipovo, Đakovo 1, Bijelo Brdo, and Vukovar) located in modern continental Croatia, 4 were classified as Bijelo Brdo, 2 as early medieval Croat, and 2 as mixed early medieval Croat and Bijelo Brdo.

Discussion

Our results demonstrated significant cranial differences among Central and South-east European medieval archaeological populations. These results complement the vast literature addressing the diversity of European gene frequencies (1,2,68). Previous investigators have focused on the links between genetic variation, as expressed in cranial morphology, and language families (3,69), cultural changes such as urbanization (70), and environmental adaptation (71). Cultural changes and environmental plasticity are not satisfactory explanations for the variation in cranial morphology noted in the analyzed series. Central and South east Europe exhibited a relatively uniform and temperate environment and significant cultural changes such as marked urbanization or a change from a primarily agricultural society to one relying on trade and manufacture did not occur until the 13th to 15th centuries. Therefore, the variations observed in cranial morphology between the analyzed archaeological series primarily reflect settlement patterns, migrations, and the ethnic affiliation of the inhabitants.

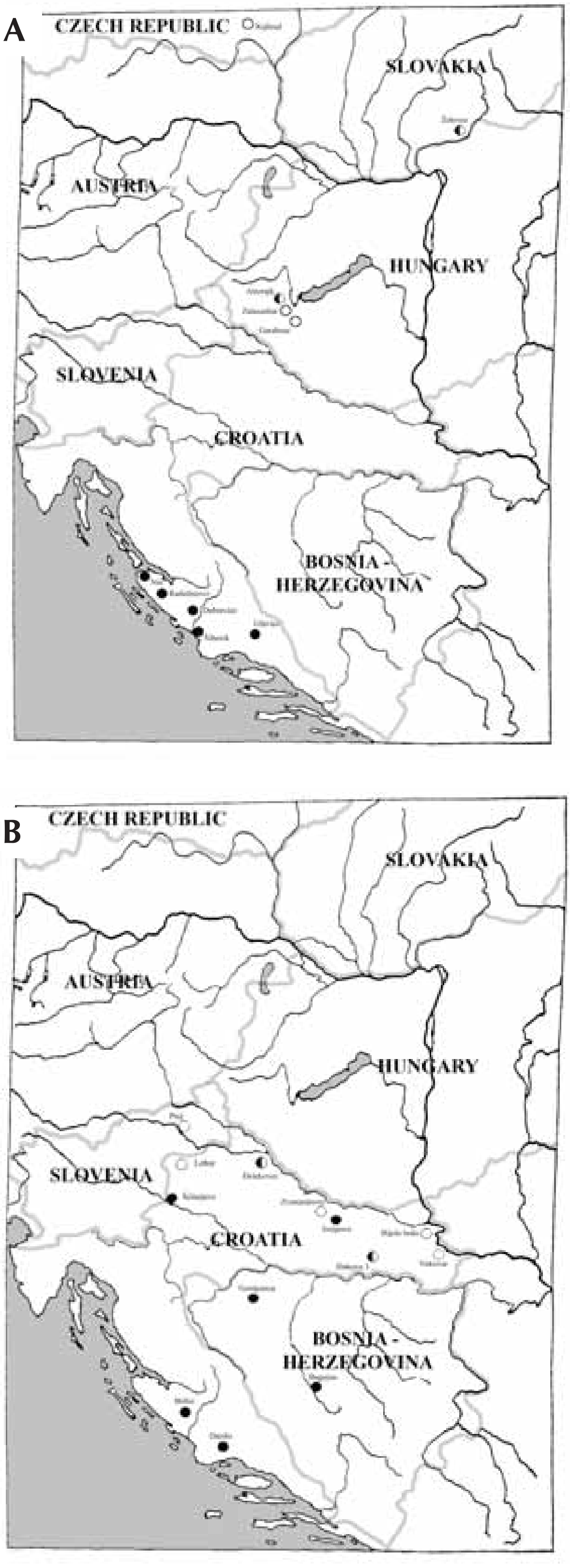

Figure 3. Medieval archaeological sites analyzed in this study. **A.** Geographical locations of sites dated from the 8th-10th centuries. **B.** Geographical locations of sites dated from the 11th-13th centuries. Black circles indicate early medieval Croat sites, white circles Bijelo brdo sites, and half filled circles indicate mixed early medieval Croat and Bijelo brdo sites. Gray lines are state borders.

Our results showed marked craniometrical similarities between early medieval Croat and medieval Polish series. Among all of the 39 analyzed European sites, the two exhibiting the greatest similarities were Nin, a site representing the nucleus of the early medieval Croat state (72), and Cedynia, a Polish site located approximately 75 km south of the Baltic Sea. Conversely, the 5 analyzed Iranian sites exhibited no similarity with the early medieval Croat sites and were all located in the diametrically opposite part of the scatter plot. These results suggest that early medieval Croats were of Slavic ancestry, and that early medieval Croats and Poles at one time shared a common homeland. Recent genetic analyses of the nonrecombining Y chromosome from 25 extant European and Middle Eastern populations support the Slavic affiliation of the Croats, and also indicate significant genetic similarities between modern Croats and Poles (1). Principal components analysis of the frequency distributions of 19 haplotypes found in the examined populations showed 3 distinct geographical and cultural clusters. The first comprised of Basque and Western European populations (French, Italian, Catalan, Andalusian, German, and Dutch), the second of Middle Eastern populations (Georgian, Turkish, Lebanese, and Syrian), and the third of Eastern European mostly Slavic, populations. This cluster included populations from Macedonia, the Czech Republic, Hungary, Ukraine, Poland, and Croatia. Of all 25 analyzed population samples, modern Croats exhibited greatest similarities with samples from the Ukraine, Hungary, and Poland.

This research has also resulted in the development of effective discriminant functions for distinguishing early medieval Croats from individuals belonging to the Bijelo Brdo culture. The accuracies achieved by the functions (89.3% for males and 97.1% for females) are similar, or slightly surpass those reported in most discriminant function analysis of crania. Howells (73) achieved better results, reaching 100% accuracy when differentiating between American Blacks and Whites, Gill and Gilbert (74) using only the mid facial skeleton obtained accuracies ranging from 82 94% when differentiating between American Blacks, Whites, and Amerindians, and more recently, using data collected from the 1991-1995 wars in Croatia and Bosnia and Herzegovina, Ross (75) achieved an accuracy of 81.7% when differentiating between modern Croats and modern Bosnians. In this study, width dimensions of the facial region (interorbital breadth, upper facial breadth, bizygomatic breadth and orbital breadth) differentiated between early medieval Croat and Bijelo Brdo males, while upper facial height, interorbital breadth, basion prosthion length, and nasal height differentiated between early medieval Croat and Bijelo Brdo females. The high levels of accuracy obtained in this study suggest a low degree of interpopulation mixture between early medieval Croats and Bijelo Brdo individuals possibly caused by geographic distance and cultural, linguistic or religious differences. Unfortunately, except for clear differences in material remains such as jewelry and pottery, little is, at present, known about potential linguistic or religious differences.

The results of these analyses are fairly consistent with the report written by the anonymous writer in the 30th chapter of the "*De Administrando Imperio*" (16). Principal components analysis suggested that early medieval Croats were of Slavic origin and shared a common homeland with early medieval Poles, possibly in modern Poland and almost certainly in "... an area north of Bavaria ..." from where they migrated to the east Adriatic coast (16). Figure 3A also showed the presence of small amounts of early medieval Croats in the former Roman provinces Illyria and Pannonia which is also consistent with the report of the anonymous writer. Figure 3B suggested that during the 11th to 13th centuries early medieval Croats expanded, first into modern Bosnia and Herzegovina, and then into modern continental Croatia where they came into more direct contact with members of the Bijelo Brdo culture. The nature of this contact is, at present, not clear. Historical sources mention anarchy and fighting. Recent analyses (76) of demographic trends and stress levels in early (6th 9th) and late (10th to 13th century) medieval skeletal series from continental Croatia showed significantly higher frequencies of periosteal lesions and cranial and postcranial traumas in adult males from the late medieval period. Males from late medieval skeletal series exhibited more than three times higher frequencies of defensive mid-shaft fractures to the ulna than males from the early medieval series. While these data are indicative of violent confrontations and a deterioration of living conditions, it is important to remember that archaeological data from the two late medieval sites in continental Croatia that included both early medieval Croat and Bijelo Brdo individuals (Đakovo 1 and Đelekovec) showed no evidence of violence or destruction. Trauma frequencies were low in both series (28) and the available evidence suggests the two groups coexisted peacefully. It, therefore, seems most probable that relationships between early medieval Croats and members of the Bijelo Brdo culture varied and changed depending on local conditions and changing political fortunes.

The conclusions relevant to the expansion of the early medieval Croats during the 10th 13th centuries need to be, however, tempered with considerable caution as they are derived from small samples. Further analysis of skeletal series from Croatia and Bosnia and Herzegovina is necessary to determine if data from these series support these observations.

Acknowledgments

This study was financially supported by the Ministry of Science and Technology of the Republic of Croatia (Grant "Development of a bioarchaeological data base for Croatia" Grant No. 0101021, Grant "The medieval archaeology of Croatia from the 5th-16th centuries" Grant No. 0197005, Grant "Archeology of the Early medieval period on the east Adriatic coast" Grant No. 0070006, and Collaborative Grant "Development of an archaeology, bioarchaeology, and paleontology data base for Croatia"). We thank Ž. Krnčević and Dr Ž. Demo for allowing us access to human osteological material from the Šibenik, Dubravice, and Bijelo brdo sites. Gratitude is also due to the three anonymous reviewers whose comments significantly improved the manuscript, as well as to the editor in chief of CMJ Dr M. Marušić for his continued support and encouragement. We also express our gratitude to two undergraduate students V. Vyroubal and Ž. Bedić who helped clean and measure the human crania.

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Received: March 17, 2004
Accepted: June 1, 2004

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